The Antiproton Source Rookie Book

Version 1.1
August, 1999

Preface

Elvin Harms, the original Pbar Operations Specialist, made the first versions of this book. I have attempted to update things that have changed, add diagrams and expand on some of the more complex subjects. The motivation for this revision is the changes associated with the replacement of the Main Ring with the Main Injector. Routine pbar operation in the Recycler Ring is not expected in the near future. Another revision will be required at that time to address the mechanics of transfers from the Antiproton Source to the Recycler Ring. Several people have assisted Elvin and I in making this document. Dave Vander Meulen assisted with CUB and stacktail cooling, Dave Olivieri and Mike Church provided guidance on the stochastic cooling chapter, Steve Anderson made the beamline component maps and Salah Chaurize made the drawing of the rings and beamlines. Others helped with proof-reading and suggested additions to the content.

Jim Morgan
August, 1999

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I. Introduction/ Why make an antiproton source?

High energy physics is a branch of science that is concerned with the constituents of matter and their interactions. The particle accelerator is a tool that is used to help the high energy physicist probe the structure of matter. An accelerator provides a high energy beam of particles that can be used to unlock short-lived subatomic particles. For a number of years the method of choice used by accelerator laboratories was to direct the beam of particles onto a stationary or “fixed” target. In the 1970’s a new method of creating the collisions was developed, colliding a beam with its antimatter counterpart in the same accelerator. By colliding beams of particles head-on, the center of mass energy of the collisions was doubled.

The first generation of colliders accelerated electrons and positrons. It wasn’t until the early 1980’s that CERN first collided protons with antiprotons. Since the proton is much more massive than the electron, higher energy collisions could be achieved (although experimenters have likened the messy collection of secondary particles resulting from the collisions to hunting through a garbage can). The SPS accelerator at CERN was used as their first collider. The center of mass energy of the collisions was initially 540 GeV (270 GeV on 270 GeV), then was later increased to 630 GeV (315 GeV on 315 GeV). With the switch to colliding beams, the SPS became the highest energy accelerator surpassing Fermilab’s Main Ring (by then a 400 GeV fixed target machine). CERN wouldn’t have that distinction for long, installation work for the Tevatron was being completed back at Fermilab.

The Tevatron began operation as an 800 GeV fixed target machine, but the eventual goal was to use it as a proton-antiproton collider. Building on the CERN innovations and experiences, Fermilab began construction on our own antiproton source. The first colliding beams in the Tevatron were established late in 1985 during a study period following a fixed target run. The antiproton source was commissioned and the first collider run began late in 1986. With a center of mass energy of 1.8 TeV (900 GeV on 900 GeV), the worlds highest energy accelerator was again found at Fermilab. CERN has since created the LEP (Large Electron Positron) accelerator and is building the LHC (Large Hadron Collider). When the LHC begins operation in the first decade of the new century, they will again posses the worlds most powerful accelerator.

Luminosity is a measure of the number of collisions at an experiment. Through a series of improvements to Fermilab's accelerator's, there has been steady improvement in the Tevatron's luminosity. During the 1988-89 Collider run, the design luminosity of $1.0 \times 10^{30} cm^{-2} sec^{-1}$ was achieved. Since that time the luminosity has increased by more than a factor of 20. With the addition of the Main Injector and other accelerator improvements, the luminosity is expected to increase by another factor of 4. The addition of the Recycler ring should bring further improvements, perhaps as much as another factor of 2.

The largest bottleneck in a proton-antiproton collider is the time required to accumulate the required number of antiprotons. The process is inherently inefficient, typically for every 10^5 protons striking a target, only 1 or 2 antiprotons are captured and stored. Considerable time and money has been spent improving the accumulation rate. Between the first collider run and collider run 1b, the peak stacking rate improved by an order of magnitude. Improvements in the antiproton source and the increased beam intensity from the Main Injector are expected to at least double the stacking rate. Despite the improvements, it still takes hours to build up a suitable stack to use for a colliding beams store. The performance of the antiproton source greatly affects the quality and duration of stores in the Tevatron.

The FNAL Antiproton Source is comprised of a target station, two rings called the Debuncher and Accumulator and the transport lines between those rings and the Main Injector. The following steps are taken in order to produce an antiproton beam suitable for a proton-antiproton colliding beams store.

- A single batch of protons with an intensity of up to 5×10^{12} is accelerated to 120 GeV in the Main Injector (MI).
- At MI flattop, the 82 or so bunches contained within the batch are rotated 90° in longitudinal phase space. The rotated bunches are extracted from the Main Injector down the P1 and P2 lines. Two Lambertson magnets and a pair of C-magnets diverts beam from the P2 line into the AP-1 line at F17, exiting the Tevatron enclosure near F18.
- The protons continue down the AP-1 line to the target vault.

In the vault the incident beam is focused to a small spot size using a series of quadrupole magnets. The beam strikes the nickel production target in the target vault and produces a shower of secondary particles

• The resulting cone of secondary particles is focused and rendered parallel by means of a Lithium lens known as the "Collection Lens". The bunch structure of the beam coming off of the target is the same as that of the primary proton beam.

• A pulsed dipole magnet bends all negatively-charged particles of approximately 8 GeV kinetic energy into the AP2 line while most of the other particles are absorbed within a beam dump.

• Particles that survive the journey down the AP2 line are injected into the Debuncher where the momentum spread of the 8 GeV beam of secondaries is reduced through bunch rotation and adiabatic debunching. Both betatron (transverse) stochastic cooling and momentum (longitudinal) cooling is applied to reduce the beam size and momentum spread.

• Just before the next pulse arrives from the target, the antiprotons are extracted from the Debuncher and injected into the Accumulator via the D to A line. Successive pulses of antiprotons are stacked into the Accumulator 'core' by means of RF deceleration and momentum stochastic cooling. The antiprotons in the core are maintained there by momentum and betatron cooling systems.

• After several hours, enough antiprotons have been accumulated to initiate a transfer to the Main Injector and Tevatron for a store (or to the Recycler via the Main Injector). Groups of 4 bunches of antiprotons are unstacked from the densest portion of the stack known as the core. The bunches are extracted from the Accumulator, and transported towards the Main Injector via the AP3, AP1, P2 and P1 lines until the desired number of antiproton bunches, nominally 36, are in the Tevatron.

II. Antiproton Production

A. Main Injector's role

Antiprotons (or pbars) are produced by bombarding a production target with a high energy proton beam. The pbar production rate is dependent on the incident beam energy and, to a much lesser extent, momentum spread. The collection efficiency is dependent on the beam spot size, the gradient of the collection lens and the aperture of the beamline. The beam spot size affects the apparent size of the area from which the secondaries emanate.

An increase in the incident beam energy will result in an increase in yield, but by a diminishing rate after a certain energy threshold is passed. Designers decided to collect a pbar beam of ~8 GeV as that is the peak Booster energy and was the standard injection for the Main Ring. Also, the peak in pbar production from a 120 GeV proton beam is near 8 GeV. A higher energy beam will continue to increase pbar yield, but an incident beam energy of 120 GeV is the best compromise between targeting efficiency, repetition rate and constraints from the transport line. Not coincidentally, 120 GeV falls into the operating range of the Main Injector. The design report calls for the Main Injector to provide 5 X 10^{12} protons per stacking cycle with a 1.5 second repetition rate. A single Booster batch comprised of 84 53 MHz bunches is accelerated in the Main Injector.

Radio Frequency (RF) manipulations are performed on the beam at 120 GeV just prior to extraction from the Main Injector in a procedure known as bunch narrowing or bunch rotation. This process, shown in figure 2.1, narrows the bunches in time at the expense of increasing the momentum spread ($\Delta p/p$). The $\Delta p/p$ of the antiprotons is minimally effected by the $\Delta p/p$ of the protons. By narrowing the bunches prior to striking the target, the phase space density of the antiprotons is maximized which results in a smaller $\Delta p/p$ in the Debuncher ring after bunch rotation and momentum cooling.

Once the beam reaches flattop in the Main Injector, the RF voltage is quickly lowered and counterphased to an effective 300 kV from its normal value of 4 MV. Main Injector RF cavities have a lower voltage limit of about 20 kV at which point electron multipactoring (sparking) occurs. Counterphasing allows the net RF voltage to be reduced to a lower level. The RF is left at this level for about 2.5 milliseconds while each bunch stretches in time, occupying a large time spread and small momentum spread.

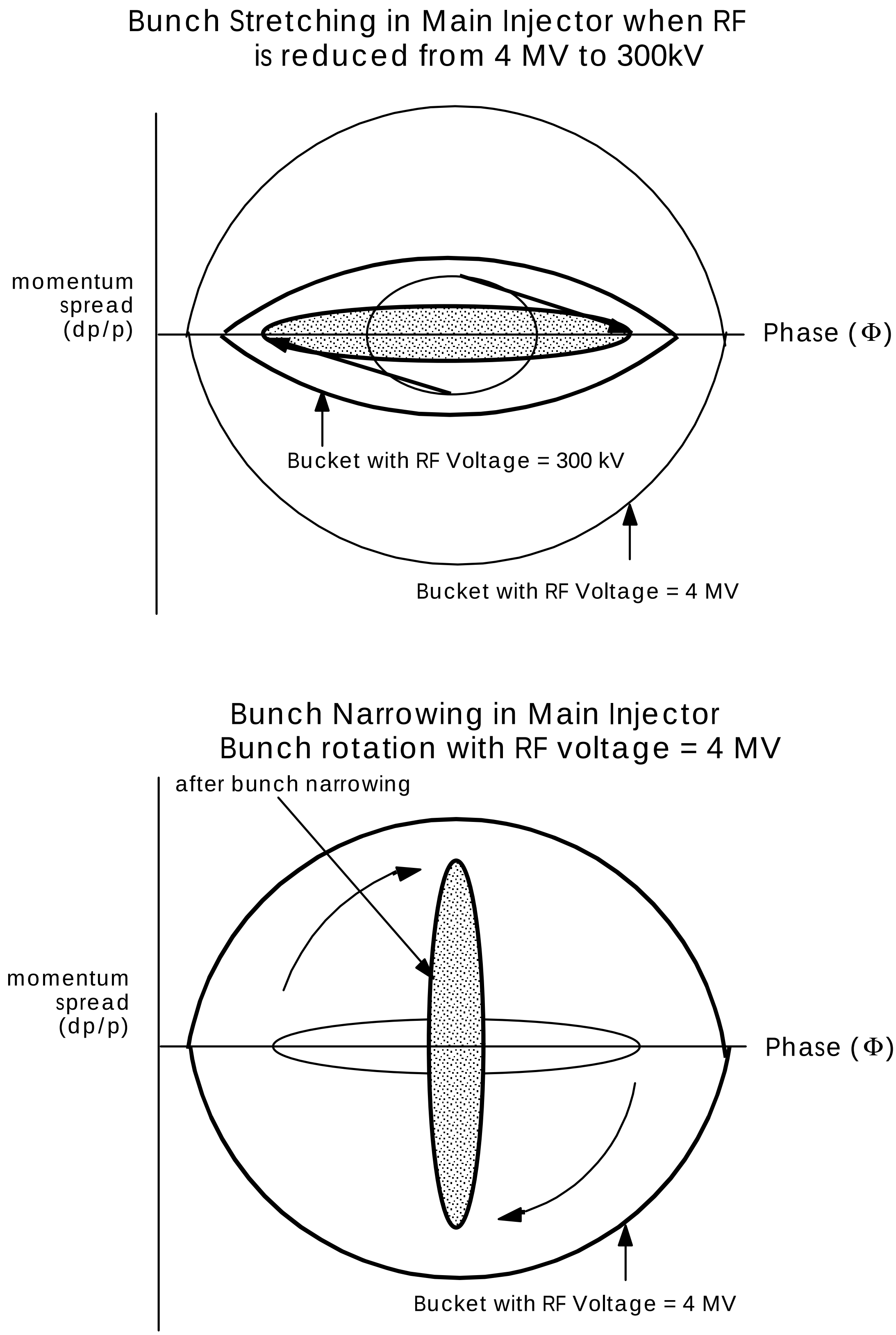

Figure 2.1 RF bunch rotation in the Main Injector

The RF is then quickly increased back to 4 MV. One quarter of a synchrotron oscillation, approximately 1.2 milliseconds later, the bunch has rotated 90° in phase space, reversing the time and momentum spread.

At this time, the beam is extracted from the Main Injector towards the pbar production target. The proton bunches have a small time spread and a large momentum spread. The extraction process is completed in a single turn by means of a fast rise time kicker located at MI-52 followed by a set of three Lambertson magnets. The extracted beam travels down the P1 line, which connects the Main Injector to the Main Ring remnant in the Tevatron enclosure. Beam passes into the P2 line at F0 and follows the path of the old Main Ring to F17. At F17 two Lambertson magnets and a pair of C-magnets bends the beam upward into the AP-1 line. The AP1 line departs the Tevatron enclosure at F18 and continues through the Antiproton source Pretarget and Prevault enclosures before reaching its terminus in the target vault. A toroid, M:TOR109, is located in the AP-1 line just upstream of the target vault to provide a measure beam intensity at the production target.

B. Target station

The actual production and collection of antiprotons occur in a specially designed vault located 17 feet below the AP0 (target) service building. The target station components are hung from 6-foot high steel modules that are suspended into the vault. This arrangement allows easy removal and replacement of faulty components and the steel provides radiation shielding. The major components as seen by the incoming beam are:

Target SEM grid - used to measure the beam position and size just prior to targeting. The SEM has motion control to move the wires out of the beam during normal operation. Beam intensity of more than a few 10^{11} could melt the SEM wires.

Target assembly - a stack of nickel disks, separated by copper cooling disks with channels for air flow to provide heat transfer. Copper targets were used for many years, but nickel can withstand a greater heat deposition before melting. Standard sized target disks are about 10 cm in diameter and 2 cm thick. Some of the targets may be extremely thin, resembling the dimensions of a CD. All disks have a hole in the middle to direct the air flow out of the assembly. The disks are held in a fixture that is encased in a thin titanium jacket.

Figure 2.2 shows the cross section of a standard target assembly used during Collider Run 1b.

The horizontal target position is adjustable (D:TRX) so that the amount of target material the beam passes through can be varied. This distance, known as the target length, is one of the parameters that determine the antiproton yield. The target assembly can be

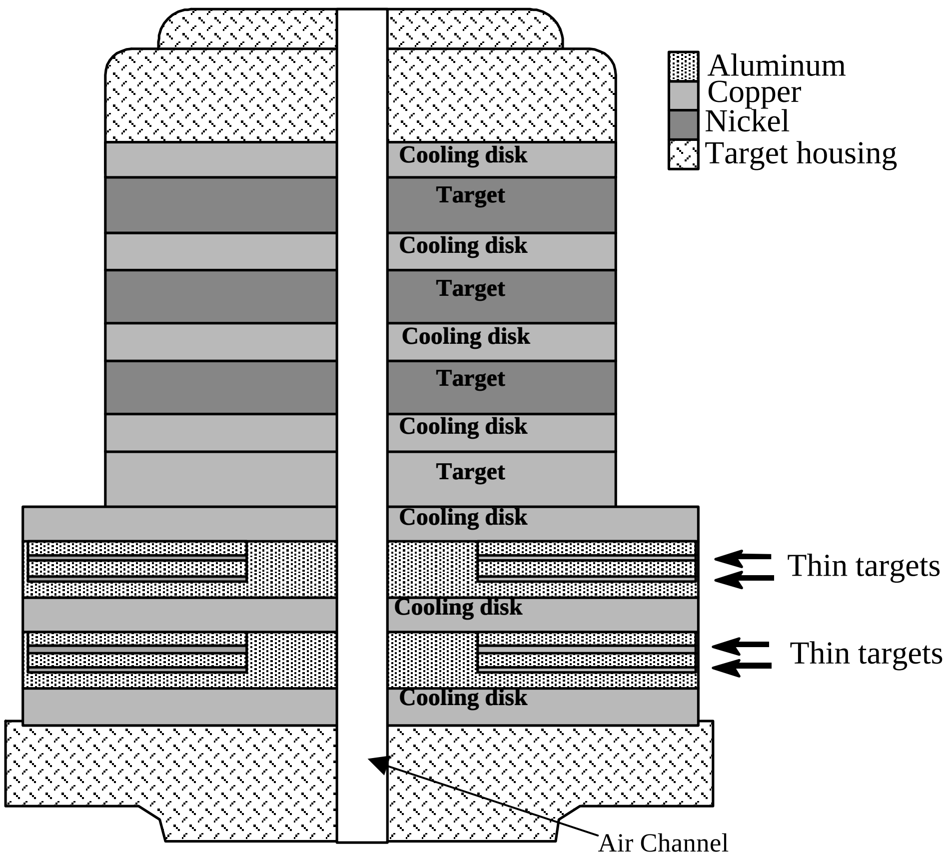

Figure 2.2 Cross section of target assembly

rotated so that potential damage to one portion of the target is minimized – depletion of the material is distributed more uniformly through the entire target. The rotation is slow, taking many minutes to complete a revolution. Vertical motion control (D:TRY) makes it possible to change the target disk in use (or to take the entire target assembly out of the path of the beam). The position of the target in the z axis (D:TRZ), the distance between the target and lens, can be adjusted to match the diverging cone of secondary particles to the focal length of the Collection lens.

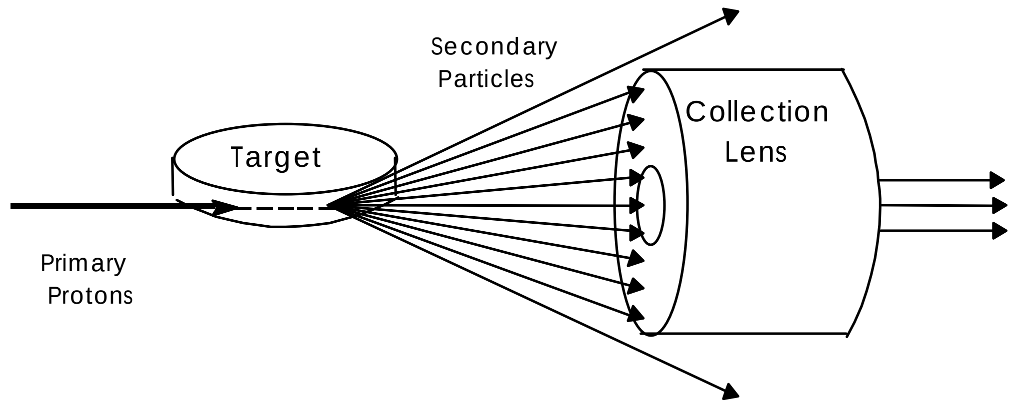

Figure 2.3 Focusing of secondary particles by the Collection Lens

Collection Lens - immediately downstream of the target module is the Collection lens module. The lens is designed to collect a portion of the secondary particles coming off of the target and render them parallel to each other (as illustrated in figure 2.3). Electric current passing through the cylindrical lithium conductor produces a solenoidal magnetic field that focuses the negative secondaries. Lithium was chosen because it is the least-dense solid conductor, which in turn minimizes scattering and absorption. The lens is contained within a toroidal transformer and is designed to operate at a peak current of 670,000A for a gradient of 1,000 Tesla/meter (operationally lenses are run at about 740 Tesla/meter to prolong their life). The transformer is used to step up the current received from the power supply (D:LNV) by a factor of 8 in order to achieve the current required. The lithium conductor is 15 cm long and 2 cm in diameter. The lens body is cooled with a closed loop cooling system. Low Conductivity Water (LCW) from the closed system is heat exchanged with chilled water. A pair of eccentric shafts is used to optimize the horizontal position and angle of the Collection lens.

Pulsed magnet - a 3-degree pulsed dipole follows the lens. Its purpose is to select 8 GeV negatively-charged particles and bend them into the AP2 line. The present magnet design is a single-turn, radiation-hardened, water-cooled, 42-inch long magnet with an aperture measuring 2.13 inches horizontally by 1.13 inches vertically.

Radiation hardening is achieved by using ceramic insulation between the magnet iron and the single winding as well as using Torlon as the insulating material on the bolts, which hold the magnet together. The pulsed magnet achieves a field of 1.5 Tesla. Figure 2.4 shows the pulsed magnet and other devices located in the target vault.

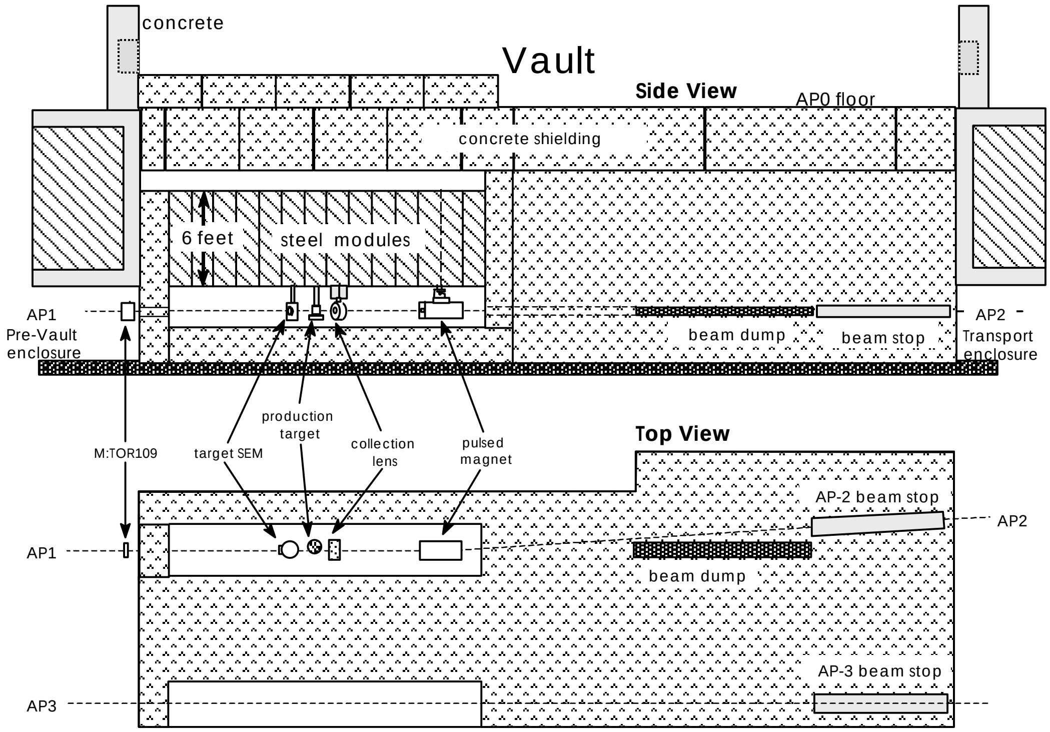

Figure 2.4 Target station components

Beam dump – most of the particles not selected by the pulsed magnet are absorbed by a graphite-core beam dump similar in design to the Tevatron abort dump. The graphite core is incased in an aluminum shell that contains water cooling channels. The graphite and aluminum make up the dump core, which is further contained within several feet of steel shielding. A channel through the steel shield provides an exit for the 8 GeV negative beam and allows it to pass into the AP-2 line. The downstream end of the dump also contains beam stops for the AP-2 and AP-3 lines (D:BSC700 and D:BSC925) which are safety system critical devices and are remotely operable.

III. Debuncher

A. Function

The purpose of the Debuncher is to accept pulses of antiprotons from AP-2 and reduce their momentum spread through RF bunch rotation and adiabatic debunching. This reduction in momentum spread is done to improve the Debuncher to Accumulator transfer because of the limited momentum aperture of the Accumulator at injection. In addition, ARF-1 and the stacktail momentum cooling system in the Accumulator are able to move the beam more efficiently when it has a small momentum spread. The Debuncher can make use of the time between Main Injector cycles to reduce the transverse beam size through betatron stochastic cooling. This greatly improves the efficiency of the Debuncher to Accumulator transfer. A momentum cooling system was later added which further reduces the momentum spread of the beam.

B. Lattice

The Debuncher 'ring' is a rounded triangle and is divided into 6 sectors numbered 10-60. Each sector contains 19 quadrupoles and 11 dipoles. Other magnetic devices include correction dipoles and sextupoles. There are three straight sections – 10, 30, and 50, which are located directly beneath service buildings AP10, 30 and 50 respectively. The even-numbered sectors serve as symmetric bridges between an odd-numbered sector and the next straight section. The straight sections are regions of low dispersion while the arcs are dispersive regions. A typical cell in the arcs is comprised of an F-quadrupole with similarly oriented sextupoles on either side followed by a dipole or drift region, then a D-quadrupole also surrounded by sextupoles of the same convention and another dipole or drift region (Figure 3.1). This is referred to as a “FODO” lattice. As is the case with straight sections in other Fermilab accelerator rings, the Debuncher straight sections contain an assortment of specialized components. The following devices populate straight section 10: the extraction kicker and septum for the D/A line, Schottky pickups (longitudinal and transverse), a beam current monitor, damper pickups and kickers and stochastic cooling pickup tanks. Stochastic cooling kickers are found in the 30 region. The 50 area is home to the AP2 line injection devices and to all of the Debuncher's RF cavities.

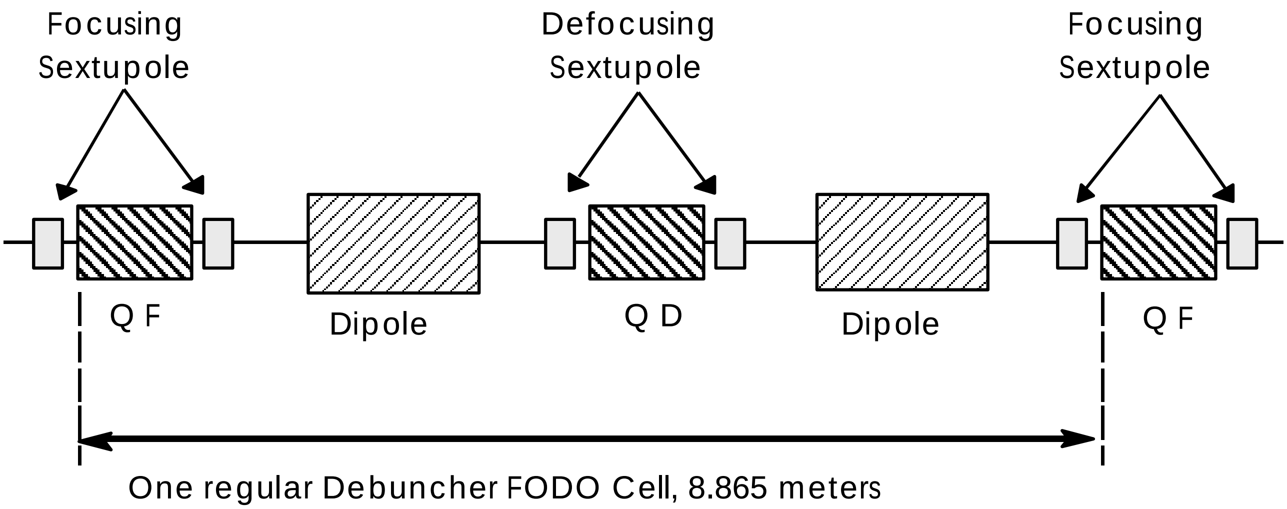

Figure 3.1 Debuncher lattice in the dispersive arcs

The numbering scheme is logical but not obvious at first glance. For example, D10Q is the first quadrupole in sector 10 (it is even in the middle of straight section 10) and is followed by D1Q2. Dipoles are numbered similarly – D1B16 is the dipole following D1Q16. Correction dipoles are labeled according to the quadrupole they proceed. Things get tricky in the even-numbered sections due to the mirror symmetry of the Debuncher lattice. The final quadrupole in D10 is D1Q19, and the next quad is D20Q (located in the center of the arc), followed by D2Q19, etc. Thus, in the direction of an antiproton beam, numbers increase in odd-numbered sectors and decrease in even-numbered sectors. The same general numbering scheme also holds true for the Accumulator, although there are fewer elements.

C. Power supplies

There are six major magnet strings in the Debuncher. The three quadrupole strings are powered by three supplies located in AP10, D:QD, D:QF, and D:QSS. D:QD powers all of the defocusing quads from DnQ6 to DnQ6 (with the exception of D6Q6). Recalling that the Debuncher lattice is FODO, D:QF, naturally, powers the focusing quadrupoles outside of the straight sections, from DnQ7 to DnQ7. D:QSS is the power supply for the

Debuncher quads in the straight sections, DnQ5 to DnQ5 (see figure 3.2), with the exception of D2Q5 and D4Q5. All magnets on the QSS bus are individually controlled by means of shunts. The Debuncher tune is changed by adjusting the D:QSn01 to D:QSn04 shunts in predetermined ratios (mults).

All of the dipoles save the correction trim dipoles are in series and are powered by D:IB, the Debuncher bend bus power supply. This supply is a very large PEI located in AP50 just inside of the west entrance. Three special quadrupoles are also powered by D:IB. These are the large quads at D2Q5, D4Q5, and D6Q6. At these locations, there must be a quadrupole in the lattice, but the small quadrupoles normally at these locations don't have a large enough aperture to accommodate both circulating and the injection or extraction beampipes. The solution was to install a large quadrupole with two beam pipes through the available aperture. The centered beam pipe is for circulating beam. The offset pipe is for injected/extracted beam, which sees a dipole field. In addition to being powered by D:IB, each of

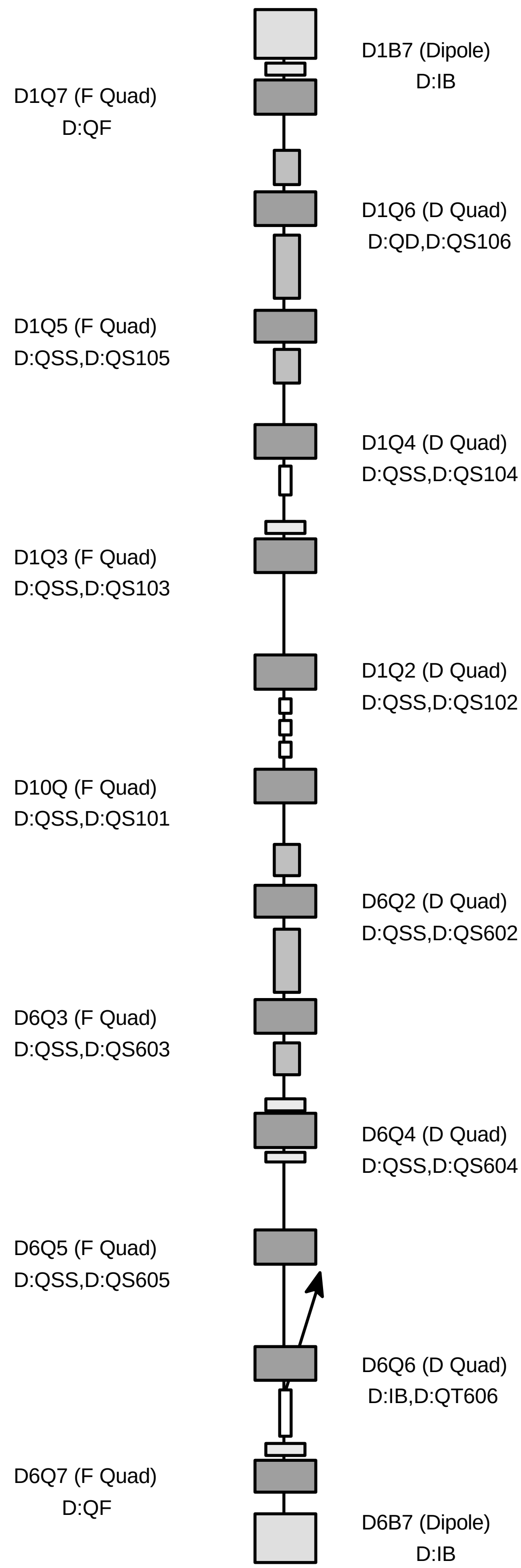

Figure 3.2 Debuncher 10 straight section

these magnets also has its own trim supply named D:QT205, D:QT405, and D:QT606 respectively. The large quadrupoles require much more current to produce the necessary field. Whereas D:QF and D:QD deliver about 240A of current, the combination of D:IB and the quadrupole trim supplies produces about 1,525A.

Additional shunts were added to the DxQ8,9,13,14,15,17,19 quadrupoles in the dispersive arcs during the Spring of 1995. These shunts, in combination with the shunts in the straight sections, are intended to be used as a "Γ_T jump". By ramping the shunts in the proper combination, the lattice (specifically the eta) can be altered to switch from the nominal lattice to one that improves the performance of the stochastic cooling. During development it was found that power supply regulation problems resulted in tune excursions and excessive beam loss so the shunts are not ramped operationally.

Sextupoles are included in the Debuncher lattice to provide chromaticity control. All of the sextupoles are powered in series on two separate buses by four supplies. Sextupoles on either side of an 'F' quad are powered by D:SEXFI and D:SEXFV. Neither supply has sufficient current nor voltage to drive the entire string, so one supply provides the necessary voltage, while the other provides current regulation. D:SEXDI and D:SEXDV do the same thing for the 'D' sextupoles.

Correction dipoles have been placed around the Debuncher to provide fine orbit control of the beam. These elements are powered by 25 Amp bipolar supplies and have been strategically placed to provide position and angle control at the extraction and injection points of the Debuncher, stochastic cooling pick-ups and locations with tight apertures.

There isn't enough room in the lattice to place correction dipoles at every location that they are needed. There are three special devices that are used to provide a dipole bump to the beam. D:BS608 is a shunt on the D6B8 main dipole magnet. Shunting current around the dipole has the effect of a horizontal trim. This shunt is normally changed along with two correction dipoles to provide a three-bump at the Debuncher extraction septa. D:MS6Q12 and D:MSD6Q7 are motor controllers on the D6Q12 and D6Q7 quadrupoles that allow the magnets to be moved vertically. Changing the vertical position of the magnet will introduce a vertical dipole bump to the beam due to quadrupole steering. These motor controllers are normally used with a vertical correction dipole to create a vertical three-bump at the Debuncher extraction kicker.

D. RF systems

Three radio frequency (RF) systems are employed in the Debuncher: DRF-1, DRF-2 and DRF-3. Table 3-1 summarizes the RF frequency, harmonic number, peak voltage and low level inputs for each system. Note that the same wide and narrow frequency band Digital to Analog Converters (DAC's) are common to all three systems.

System	Freq.	Harm.	Peak Voltage	Amplitude	Frequency
DRF-1	53.1 MHz	h=90	5.5 MV	DAC (D:R1LLDA) 164 card (D:R164AM)	DAC (D:R1LLFR) wide or narrow
DRF-2	2.36 MHz	h=4	500 V	DAC (D:R2LLAM)	DAC (D:R1LLFR) wide or narrow
DRF-3	2.36 MHz	h=4	800 V	DAC (D:R3LLAM) 164 card (D:R364AM)	DAC (D:R1LLFR) wide or narrow 164 card (D:R364FR)

Table 3.1 Debuncher RF systems

1. DRF-1

DRF-1 is a 53.1 MHz system (h=90) used for bunch rotation and adiabatic debunching of antiproton pulses injected into the Debuncher. Recall that bunch rotation in the Main Injector was done to reduce the phase space occupied by the antiprotons created at the target station. DRF-1 accepts the short (in time) pbar bunches coming from the target, rotates them in phase space resulting in bunches of antiprotons with a large time spread and a small momentum spread. The beam is then adiabatically (slowly) debunched over 60 milliseconds by lowering the RF voltage.

There are a total of eight DRF-1 cavities of two varieties: six so-called 'Rotators' and two 'Adiabatic' cavities. The six rotator RF cavities are able to operate at a peak voltage of approximately 1 MV each. In order to rapidly reduce their voltage, the RF drive signal is inverted just long enough for the fields in the cavity to be forced to zero. This rapid reduction in voltage is necessary in order for the cavities to quickly pass through the range where they may multipactor, or spark. As the voltage on the six main cavities is reduced, the voltage on the other two cavities is slowly lowered from 100 kV to achieve debunching. These adiabatic cavities are of a somewhat different design to prevent multipactoring. The modifications consist mainly of a ceramic accelerating gap to isolate the beam pipe vacuum from the air in the cavity. This ceramic limits the peak voltage across the gap to about 150 kV. Figure 3.3 shows the total DRF-1 voltage during the debunching process.

DRF1 is initially phase-locked to MIRF to provide for a bucket to bucket transfer. The 8 GeV secondary particles created at the target retain the same bunch structure as the 120 GeV protons. The DRF1 rotator cavities are pulsed just before beam arrives in the Debuncher. When timed correctly the RF will reach peak voltage at the time beam is injected. The large bucket area creates a mismatch, as it is much larger than the phase space area of the beam. The rotator cavities only pulse for approximately 200 µs (.2 ms)

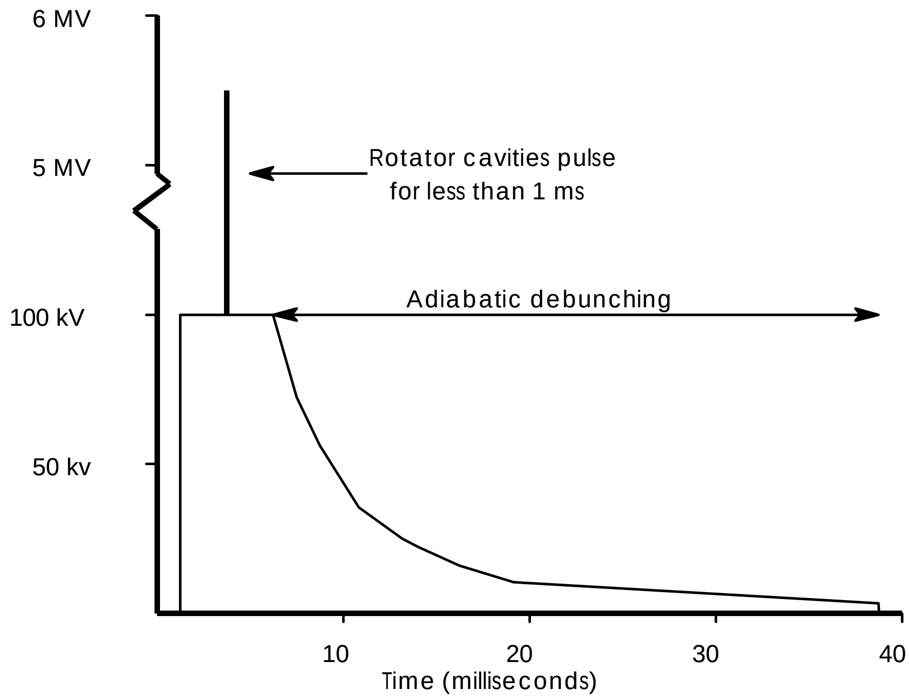

Figure 3.3 DRF-1 cavity voltage during debunching

compared with the 36 ms that the adiabatics are on.

Because of the mismatch, the bunches rotate in the bucket as illustrated in figure 3.4. The rotator cavities are turned off after the bunches have rotated about 45° in phase space, they rotate an additional 45° during the adiabatic debunching process. Note that the rotator cavities pulse for only 200 µs but put out a collective 5.1 MV. The two adiabatic cavities are on for

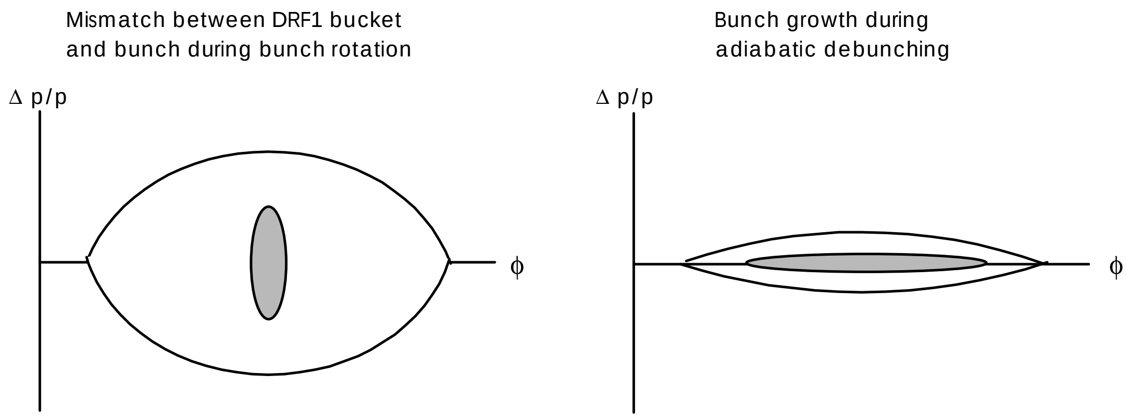

Figure 3.4 Bunch rotation in the Debuncher

about 36 ms, but only put out a combined 100 kV before the voltage is gradually lowered.

The RF amplitude for DRF1 is divided into separate control for the rotator and adiabatic cavities. The adiabatics are normally controlled by a waveform generator (Camac 164) card but can also be run Continuous Wave (CW) with a DAC. The RF amplitude that the rotator cavities are pulsed to is controlled by a series of 6 DAC's, one for each cavity.

The frequency signal comes from one of two Voltage Controlled Oscillators (VCO's), a wideband VCO for studies, or a narrow band VCO used for normal operation. During stacking, the VCO is initially phase-locked to the Main Injector RF and stays at a fixed frequency. This frequency is generally set at the beginning of a running period and remains unchanged. For several years the DAC has been set to 53.10312 MHz. Since DRF1 is an H=90 system, this corresponds to a revolution frequency of 590,035 Hz. It is important that the beam injected into the Debuncher from the Main Ring has this revolution frequency as DRF1 and the momentum cooling will not work as well if the frequency varies significantly.

The bunch rotation efficiency provides a measure of how small the momentum spread of the antiprotons is shortly after DRF-1 is turned off. The parameter D:FFTEFF is derived by the pbar FFT from the Debuncher longitudinal schottky detector. Typical efficiencies are in the 75-85% range. Two parameters can be tuned to maximize the bunch rotation efficiency. D:R1LLPS is the phase offset between the Main Injector and Debuncher low level RF and is tuned to optimize bucket to bucket transfer. D:R1LLMT is the master trigger time and controls when the DRF-1 rotator cavities are pulsed. By synchronizing the peak RF voltage (and bucket area) to the arrival of the beam, capture can be maximized. Qualitatively, the bunch rotation display on Cable Television (CATV) Pbar channel 30 gives a good indication of the rotation efficiency (see figure 3.5).

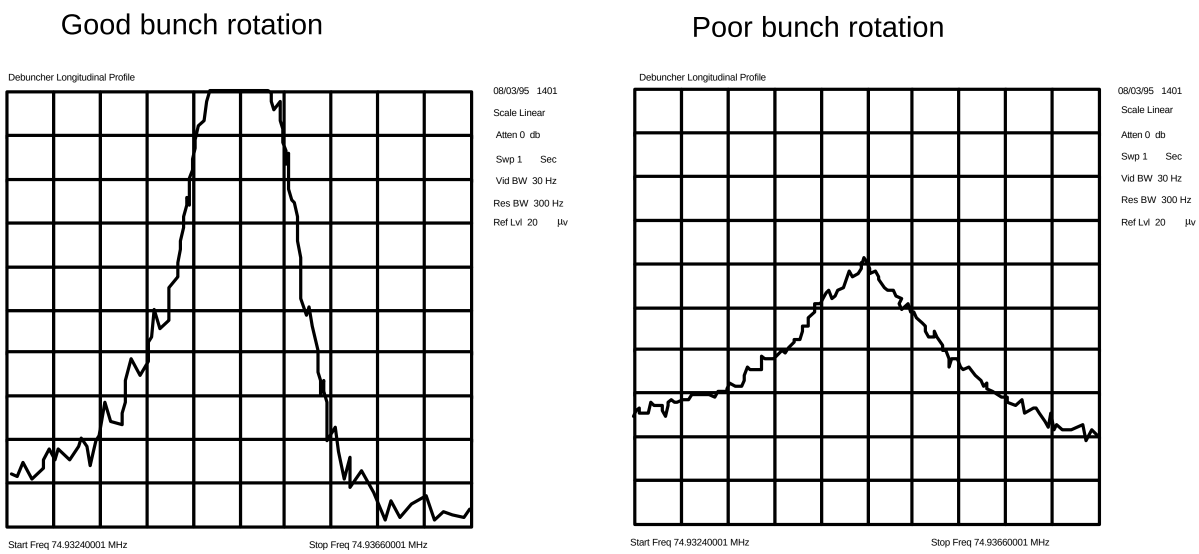

Figure 3.5 Debuncher spectrum analyzer displays

2. DRF-2

The Debuncher circumference is larger than that of the Accumulator (and the Booster) by 7.1%. The Debuncher 53 MHz harmonic number is 90, while the Accumulator's is 84. Debuncher to Accumulator transfer efficiency is optimized by maintaining a gap in the Debuncher beam. This is so that upon transfer the beam just fits around the circumference of the Accumulator. When properly timed, the Debuncher extraction kicker rise time occurs in the gap. The 200 nanosecond gap (compared to the revolution frequency of 1.69 µs) is preserved by DRF-2, which forms a 'barrier bucket' that excludes particles from its interior. DRF-2 is timed to preserve a gap between the leading and trailing pbar bunches entering the Debuncher.

The period of the applied RF wave is one quarter of the Debuncher rotation period, making it an h=4 system. The nominal frequency is thus 2.36 MHz. The gap electrodes are phased apart for one RF cycle during each revolution, then phased together for the remaining 3/4 revolution for zero effective voltage. The fact that the accelerating field is suppressed for part of each revolution is precisely the reason this type of radio frequency system is dubbed a 'suppressed bucket' RF system.

Referring to figure 3.6, a normal RF bucket keeps the particles within the bucket by accelerating low momentum particles and decelerating high momentum particles. In the barrier bucket example, the phase of the RF wave is shifted 180°. Higher momentum particles are accelerated upon entering the barrier bucket region, and lower momentum particles are decelerated which effectively excludes beam from the barrier bucket.

DRF-2 has a DAC that provides the amplitude program (D:R2LLAM). DRF-2's maximum voltage is approximately 500 V although it normally runs in the 200 - 400V range.

The same VCO used by DRF-1 is also used by DRF-2 (and DRF-3). The DRF-2 frequency (2.36 MHz instead of 53.1 MHz) is derived by dividing the output of the VCO by 22.5.

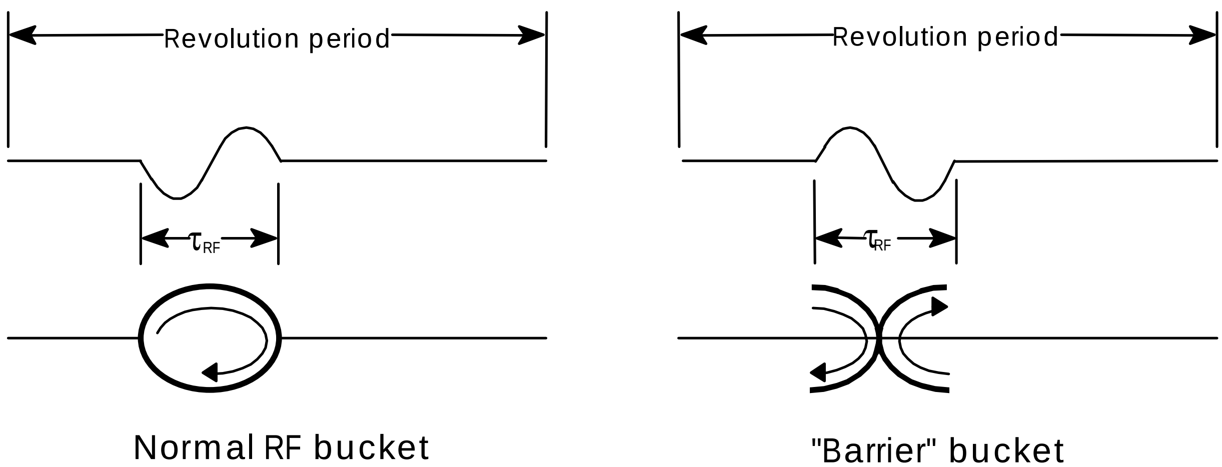

Figure 3.6 DRF2 Barrier bucket

3. DRF-3

The third and final RF system found in the Debuncher is also an h=4 system. In this case, however, no buckets are suppressed. DRF-3 is used only as an aid during studies and is primarily used to move the beam to permit full exploration of the Debuncher momentum aperture. It operates at up to 800 Volts.

Amplitude control for DRF-3 is provided by either a DAC or a 164 card, although the latter is rarely used. Frequency control is provided by either a 164 card or the same VCO's as DRF-1 and DRF-2 (again the 164 card is rarely used). As with DRF-2 the frequency from the VCO is divided by 22.5 to change the RF frequency from 53.1 MHz to 2.36 MHz. The wideband VCO is generally used with DRF-3 during studies to provide enough range to move the beam across the aperture.

IV. Accumulator

A. Function

The purpose of the Accumulator, as its name implies, is to accumulate antiprotons. This is accomplished by momentum stacking successive pulses of antiprotons from the Debuncher over several hours or days. Both RF and stochastic cooling systems are used in the momentum stacking process. The RF decelerates the recently injected pulses of antiprotons from the injection energy to the edge of the stack tail. The stack tail momentum cooling system sweeps the beam deposited by the RF away from the edge of the tail and decelerates it towards the dense portion of the stack, known as the core. Additional cooling systems keep the pbars in the core at the desired momentum and minimize the transverse beam size.

What follows is a chronological sequence of events that takes place in the Accumulator:

1) Unbunched antiprotons are extracted from the Debuncher, transferred down the Debuncher to Accumulator (D/A) line, and injected into the Accumulator with a kinetic energy 8 GeV. The beam is transferred in the horizontal plane by means of a kicker and pulsed magnetic septum combination in each machine (in order: D:EKIK, D:ESEPV, A:ISEP2V, A:ISEP1V and A:IKIK). Extraction in the Debuncher occurs just before another antiproton pulse arrives from the target.

2) The Accumulator injection kicker puts the injected antiproton pulse onto the injection closed orbit which is roughly 80mm to the outside of the central orbit. The kicker is located in a high dispersion region so the higher energy injected beam is displaced to the outside of the Accumulator. This kicker is unique in that there is a shutter which moves into the aperture between the injection orbit and the circulating stacktail and stack. The shutter is in this position only when the kicker fires. The shutter's purpose is to shield the circulating antiprotons already in the Accumulator from fringe fields created when the kicker fires. Figure 4.1 diagrams a spectrum analyzer display of the Accumulator longitudinal beam distribution as seen on CATV pbar channel 29 and shows the

relative location of the shutters in revolution frequency (which relates to the horizontal position in a dispersive region).

3) After the injected pbars have been kicked onto the injection closed orbit, the shutter is opened and a 53 MHz RF system known as ARF-1 captures the beam in 84 bunches. ARF-1 then decelerates the beam by approximately 60 MeV to the edge of the stack tail, beyond the space occupied by the kicker shutter. The RF is adiabatically (very slowly) turned off as the edge of the tail is

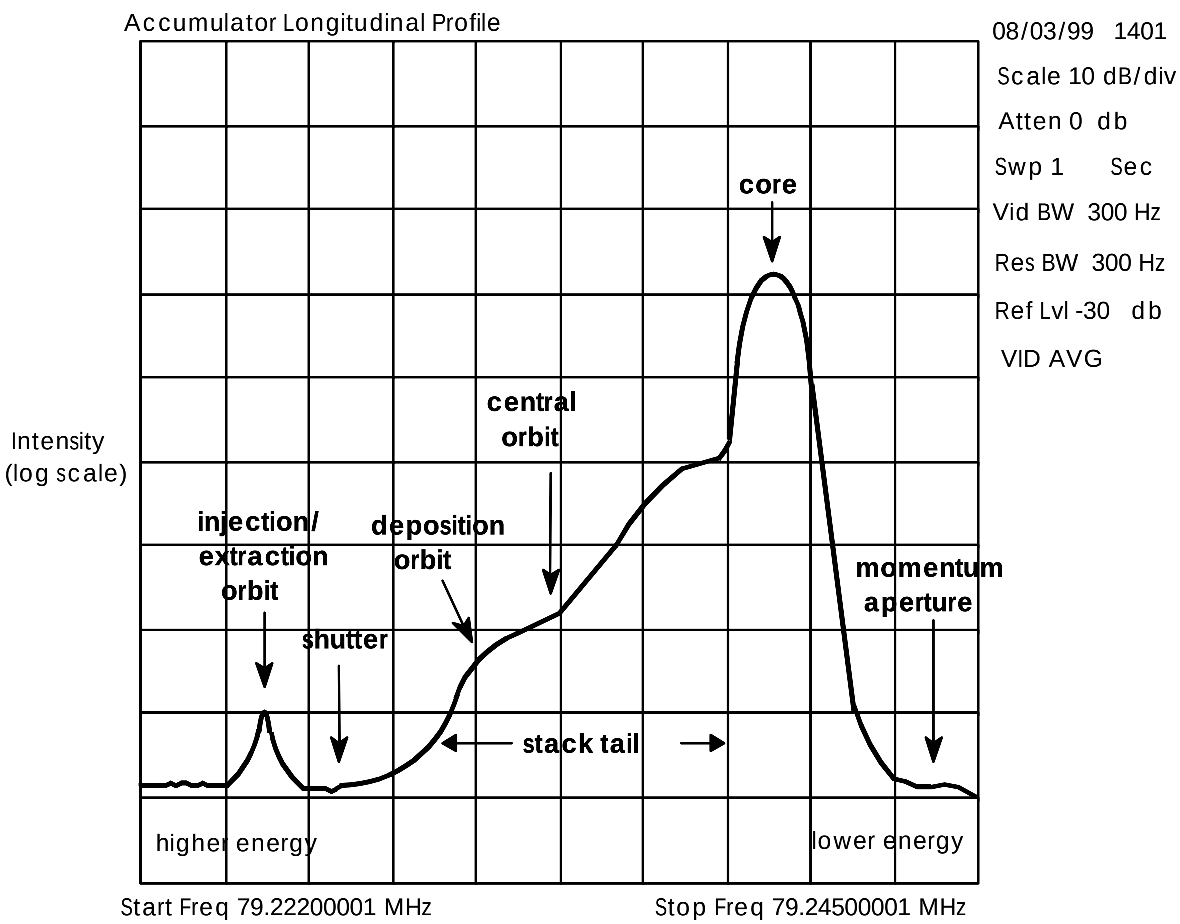

Figure 4.1 Accumulator stack profile

approached and the now unbunched pbars are deposited into the stack tail.

4) The stack tail momentum cooling system now acts on the pbars. This system decelerates the beam towards the stack core which is approximately -150 MeV from the injection orbit (or ~63 mm to the inside of the Accumulator central orbit in a high dispersion region).

5) After approximately 30 minutes, the antiprotons in the stack tail have been decelerated into the domain of the core cooling systems. Six stochastic cooling systems act on beam in the core during stacking. The 2-4 GHz and 4-8 GHz core momentum systems control the momentum spread and keeps the pbars from hitting the low momentum aperture. The 2-4 GHz and 4-8 GHz core horizontal and vertical betatron cooling systems keep the transverse emittances minimized.

6) This process continues for hours or days with the stack growing in size until the desired Accumulator intensity is reached or the Tevatron needs to be refilled.

7) When a transfer of pbars to the Main Injector is desired, an RF system known as ARF-4 is utilized. ARF-4 has a harmonic number of h=4 and is energized at a very low amplitude at a frequency corresponding to that of the revolution frequency of beam in the core. The RF voltage is slowly increased and a portion of the beam in the core is captured into four buckets and is slowly moved through the stack beyond the space occupied by the shutter, and onto the extraction orbit (at the same frequency as the injection orbit).

8) Once the unstacked bunch is on the extraction orbit, the ARF-4 voltage is increased. The additional voltage acts to shrink each bunch longitudinally, giving them the same distribution in time as 10-12 Main Injector 53 MHz bunches.

9) Just before the extraction kicker is fired, ARF-1, is energized and the antiprotons destined for the Main Injector are rebunched into 11 or so bunches suitable for capture by MIRF.

10) The extraction kicker shutter closes, then the kicker is fired. Like its injection counterpart, the extraction kicker has a shutter to shield the remaining stack from fringe fields. The deflection imparted by the kicker provides sufficient horizontal displacement to place the kicked beam in the field region of a Lambertson magnet in straight section 30 which bends the beam up out of the Accumulator and into the AP3 line.

B. Lattice

The Accumulator “ring” actually resembles a triangle with flattened corners. The lattice has been designed with the following constraints in mind.

- The Accumulator must be capable of storing an antiproton beam over many hours.
- There must be several long straight sections of lengths up to 16 m with small transverse beam sizes to accommodate stochastic cooling pickups and kickers.
- Some of these sections must have low dispersion, others with dispersion of about 9 m (high dispersion).
- Betatron cooling pick-ups and kickers must be an odd multiple of $\pi/2$ apart in betatron phase (i.e. the number of betatron oscillations) and far enough apart physically so that a chord drawn across the ring will be significantly shorter than the arc. Cooling pickup signals must arrive at the kickers on the same turn in time to act on the particles that created the signal.

The end result is that the Accumulator has an unconventional triangular shape that includes 6 straight sections with alternately low and high dispersion. This shape was considered most efficient as compared to other designs, which were up to 10-sided.

The reader may wonder what the need is for high and low dispersion sections or what the difference is. The dispersion function (often written η_x or η_y) describes the contribution to the transverse size of a particle beam as a result of its momentum spread. Dispersion is caused in large part by bending magnets, different momenta particles are bent at different angles as a function of the momentum. In a low dispersion area, the beam size is almost entirely defined by the β function and the normalized emittance of the beam. In a high dispersion region, the beam size is defined by the β function and normalized emittance as well as the dispersion function. In the case of the Accumulator, the horizontal β function is largest in the high dispersion regions in addition to the large horizontal dispersion function. As a result, the beam size is very small in the low dispersion areas and very wide horizontally in the high dispersion areas (there is very little vertical dispersion due to the fact that there are only small vertical trim dipoles in the Accumulator). Normalized emittance, often written as ε_n, describes the

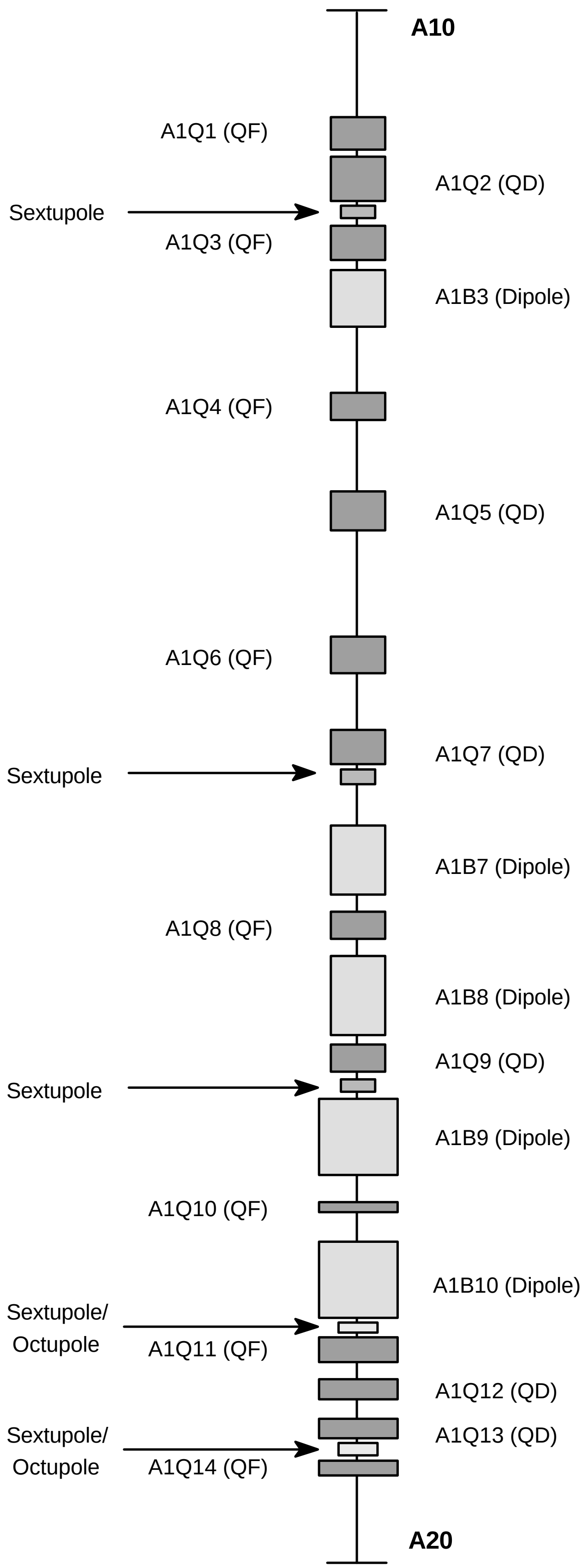

Figure 4.2 Accumulator lattice

transverse size of the beam independent of the beam energy, β function and dispersion function.

Low dispersion regions can be used by cooling systems to sense a beam position error due to transverse oscillations. In a similar vein, position errors in a high dispersion section can in large part be attributed to off-momentum beam. In the case of the Accumulator, betatron cooling system pickups are best placed in low dispersion straights while momentum cooling pickups are found in one of the high dispersion straight sections.

The lattice of the Accumulator, shown in figure 4.2, is much different from the Debuncher. There are special arrangements of quadrupoles approaching the straight sections in order to achieve the desired dispersion. Like the Debuncher, the Accumulator has mirror symmetry about the straight sections. The magnet numbering scheme increases as one travels in the pbar direction in the odd-numbered sectors, and decreases in the even sectors. Like the

Debuncher, the Accumulator straight sections are full of specialized devices. A10 contains core betatron cooling pickup tanks, Schottky and other diagnostic pickups, damper pickups and kickers as well as the beam current transformer for measuring the circulating beam intensity. The injection and extraction kickers are found in straight section 20 as are the pickup arrays for the 4-8 GHz core momentum cooling system. In A30 reside the extraction Lambertson magnetic septum, the stack tail momentum, 2-4 GHz core momentum, and core betatron cooling kickers. Section 40 contains a beam scraper used for measuring $\Delta p/p$ and a set of flying wires for making high dispersion measurements of the beam size. A50 contains transverse scrapers as well as space for detectors for E835 or other experiments. The various Accumulator RF cavities are also found in A50. Just upstream of the actual straight section is the kicker tank for the 4-8 GHz core momentum system and a set of flying wires for making low dispersion measurements of the beam size. Straight section 60 contains all of the stochastic cooling pickups for the stack tail momentum systems and the 2-4 GHz core Δp cooling pickups.

C. Power supplies

The main dipoles and quadrupoles in the Accumulator are powered by 5 different power supplies, A:QT is located in AP10 and the others are located at AP50. All of the dipoles are powered in series by A:IB, a large 12-phase PEI supply. Like D:IB, it has a separate 13.8 kV transformer outside of the building. The setting of the A:IB power supply is not changed arbitrarily. The nominal bend field is closely coupled to both the Debuncher and the Main Injector. The Debuncher main dipole field is set to provide pbars at the correct injection frequency of the Accumulator. The extraction revolution frequency of the Accumulator must be matched to the Main Injector injection energy. The Accumulator bend field is only changed after checking for an energy mismatch between the Main Injector and the Accumulator.

The 'large' quadrupoles, the ones found on either side of the high dispersion straight sections numbered ten through fourteen, are all powered by A:LQ. Similarly, quadrupoles adjacent to the low dispersion sections, the first through third quads in a sector, as well as the six location quads, are connected to the A:QT bus. Outside of the straight sections one finds alternately focusing and defocusing quadrupoles. With the exception of the six location, these are all powered by a single supply, A:QDF. Current is delivered to each type of quad after passing through one of two shunts on the output of this supply. A:QSF1 shunts current from the focusing quads, A:QSD is the shunt for the defocusing quadrupoles. The current delivered to the focusing and defocusing quadrupoles differs by a few percent at most. The Accumulator tunes are varied by changing all of the above quadrupole devices simultaneously in a predetermined ratio (mult).

As a cost-cutting measure, the Accumulator magnets were built to provide fields for 8 GeV particles, hence run close to or at magnetic saturation at 8 GeV. For this reason, changes to the bend and quad buses should not be made lightly as hysteresis effects may be significant. To provide for reproducible tunes and orbits, the major supplies are "cycled" or ramped from nominal to zero current three times following any period when the supplies have been turned off (like for an access) or their values changed significantly (such as during deceleration for E835).

In addition to dipoles and quadrupoles, higher order correction element strings can be found in the Accumulator. Five sextupole supplies known as A:SEX3, A:SEX7, A:SEX9, A:SEX10, and A:SEX12 power sextupole magnets located adjacent to the third, seventh, ninth, tenth and twelfth quadrupoles in each cell. Octupoles are found near the tenth and twelfth quads and are powered respectively by A:OCT10 and A:OCT12. In fact, the sextupole and octupole magnets in the '10' and '12' locations are wound on the same frame, the fields being formed by the shape and location of the windings rather than the number of poles.

Three other supplies deserve mention: decoupling of the horizontal and vertical tunes is possible by means of two skew quadrupole magnets powered by A:SQ100 and A:SQ607. Both supplies have reversing switches, which make it possible to reverse the polarity of either magnet. Finally, there is the extraction Lambertson magnet powered by D:ELAM. This supply is kept on during normal Collider operation despite the fact that it is needed only during reverse injection of protons and transfers of antiprotons. The higher order fields produced by the Lambertson are sufficiently strong in the 'field-free region' so as to cause noticeable tune and coupling differences when on versus off.

Fine control of the Accumulator orbit is possible by means of a combination of trim dipoles, dipole shunts and motorized dipoles. Each main dipole in the Accumulator has a shunt, permitting individual control of the current passing through each, providing some horizontal orbit control. The shunts can be used in combination with other shunts or horizontal trims to produce local bumps. Due to space limitations, the AxB8 and AxB10 dipole magnets have stepping motors on their magnet stands allowing them to be rolled slightly. Rolling the dipole imparts a vertical deflection on the beam and can be used in place of a vertical trim magnet. Both horizontal and vertical trims are located near beam transfer points. Vertical trims are also located in the arcs.

System	Freq.	Harm.	Peak Voltage	Amplitude	Frequency
ARF-1	52.8 MHz	h=84	80 kV	DAC (A:R1LLAM) 164 card (A:R164AM)	DAC (A:R1LLFR) 164 card (A:R164FR)
ARF-2	1.26 MHz	h=2	200 V	DAC (A:R2LLAM) 164 card (A:R264AM)	DDS (A:R2FSET) 468 card (A:R268FF)
ARF-3	1.26 MHz	h=2	6,000 V	DAC (A:R3LLAM) 164 card (A:R364AM)	DDS (A:R2FSET) 468 card (A:R268FF)
ARF-4	2.5 MHz	h=4	1,000 V	DAC (A:R4LLAM) 466 card (A:R466A)	DDS (A:R2FSET) 468 card (A:R268FF)

Table 4.1 Accumulator RF systems

D. RF systems

1. ARF-1

The Accumulator has four RF systems, ARF-1, ARF-2, ARF-3 and ARF-4. Table 4.1 summarizes attributes of the various Accumulator RF systems. ARF-1, the 52.8 MHz (h=84) system, serves a dual purpose, used both for stacking and transfers to the Main Injector. Figure 4.3 shows the voltage and frequency waveforms used during stacking. When stacking, ARF-1 is used to move beam from the injection orbit across the kicker shutter aperture to the high energy edge of the stack tail (deposition orbit). This process takes about 430 milliseconds. As beam from the Debuncher enters the Accumulator, it is a nearly continuous stream with a small momentum spread and no bunch structure. In order to efficiently capture the beam, ARF-1 bunches the beam adiabatically. The phase is then shifted ~0.6 degree and the frequency increased by ~10 kHz to decelerate the beam to the edge of the stack tail. Next, the beam is debunched by adiabatically reducing the RF voltage. The antiprotons experience an energy reduction of 0.7%.

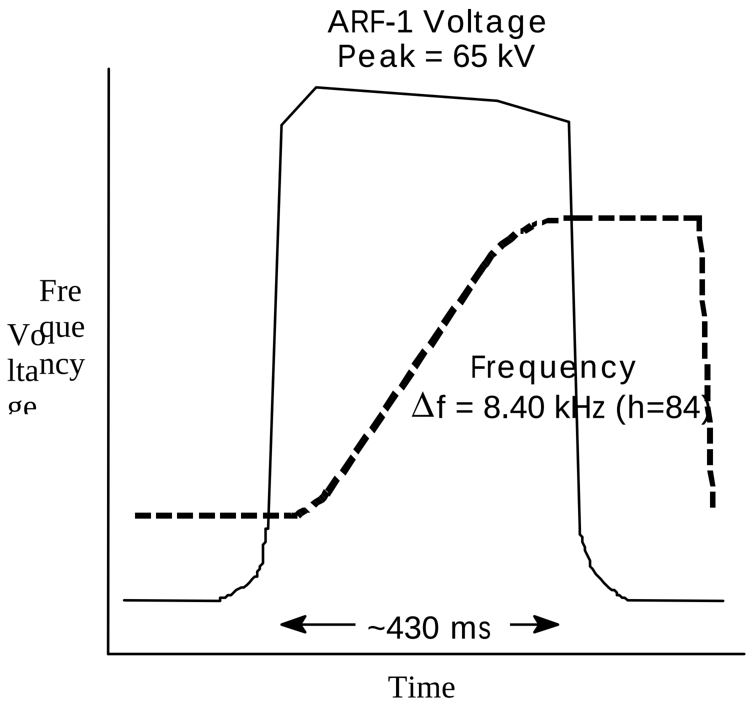

Figure 4.3 ARF-1 Waveforms for Stacking

Transfers of antiprotons back to the Main Injector are accomplished by means of a bucket to bucket (synchronous) transfer (pbars could be adiabatically bunched in the Main Injector, but poor 8-GeV lifetime made the option less desirable). For synchronous transfer, the bunch structure of the extracted pbars must be compatible with the Main Injector RF bucket structure. ARF-1 was designed as a 52.8 MHz h=84 machine to serve this purpose. After beam arrives on the extraction orbit, the ARF-1 voltage is raised in 450 milliseconds to 65 kV to impart the 52.8 MHz structure on the beam.

Antiprotons are extracted from the core by ARF-4 as four h=4 bunches, as will be detailed below. ARF-1 is turned on shortly before extraction and gives the antiprotons a 52.8 MHz bunch structure. The net result is four sets of approximately eleven 52.8 MHz bunches being transferred to the Main Injector. Eleven bunches is about the largest number of bunches that the Main Injector can coalesce efficiently. A larger increase in ARF-4 voltage prior to extraction would further narrow the bunches (fewer 52.8 MHz bunches would be created) but at the cost of a larger dp/p for the individual 52.8 MHz bunches. Figure 4.4 shows the voltage and frequency waveforms used to bunch the unstacked beam just prior to transfer. To facilitate a synchronous transfer, ARF-1 is phase-locked to Main Injector/Recycler low level RF.

The amplitude reference for ARF-1 can be switched to either a DAC (A:R1LLAM) or a 164 card (A:R164AM). The frequency inputs also are provided by both a DAC (A:R1LLFR) or a 164 card (A:R164FR). The 164 card is phase locked to the Direct Digital Synthesizer (DDS) used by ARF-4 during unstacking. A Sciteq frequency oscillator can also be switched in but is only used during studies.

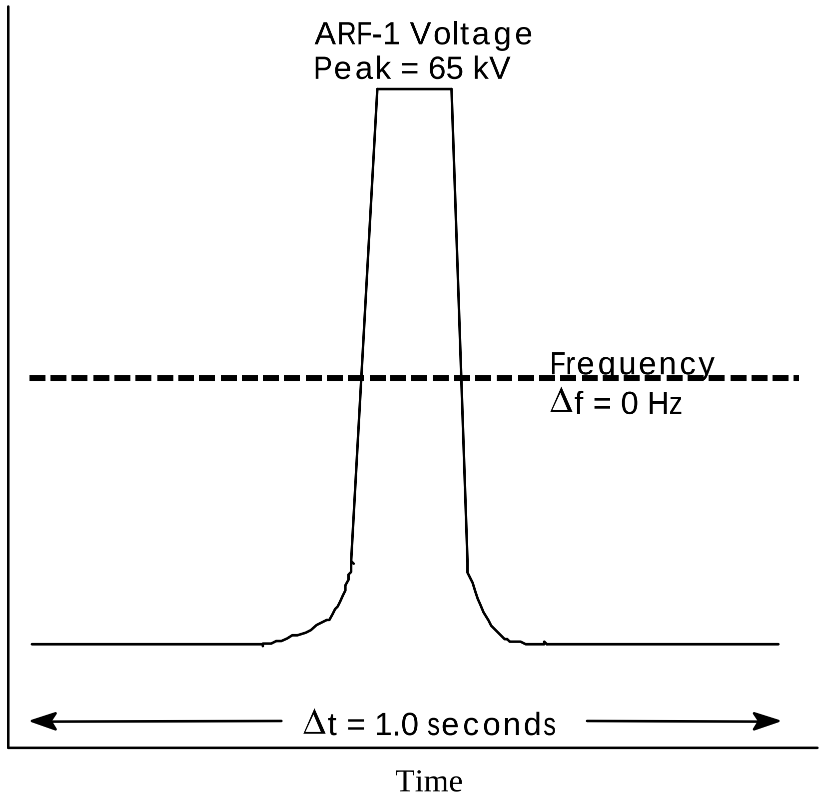

Figure 4.4 ARF-1 Waveforms for Antiproton transfers to the Main Injector

2. ARF-2

ARF-2 was originally used to unstack beam from the core during collider operation. The shift from 6 proton on 6 antiproton bunch operation to 36 on 36 operation required a more timely means of transferring the antiprotons. By removing the pbar bunches four at a time with ARF-4, only 9 unstacking sequences are required instead of 36. ARF-2 is an h=2, 1.26 MHz system that has one of the two buckets suppressed in a manner similar to DRF-2, but not using a barrier bucket (see figure 4.5). This is accomplished by a module, which suppresses every other RF cycle and sends the resultant wave to the high level.

Amplitude control of ARF-2 can be switched to either a DAC (A:R2LLAM) or a 164 card (A:R264AM). The frequency inputs are provided by a DDS which can be set to a DC level (A:R2FSET) or driven by a 468 card

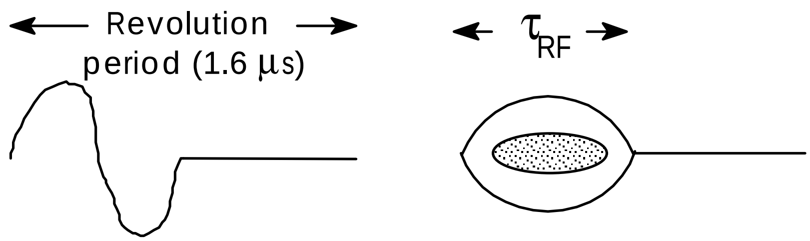

Figure 4.5 ARF-2 structure

(A:R268FF). Note that A:R2FSET and A:R268FF are simultaneously used for the ARF-2,3 and 4 reference.

The primary function for ARF-2 now is for "stabilizing RF" to minimize the number of trapped positive ions in the Accumulator. Approximately 10-20V of RF is applied at the core revolution frequency to weakly bunch the beam. This bunching of the beam acts to dislodge trapped positive ions from their potential wells.

3. ARF-3

ARF-3 was used for many years to narrow bunches on the extraction orbit. With the advent of ARF-4, ARF-3 is no longer used in the extraction process. ARF-3 operates at 1.26 MHz and h=2, it does not have a suppressed bucket like ARF-2 (see figure 4.6).

Now the primary use for ARF-3 is for decelerating stacks for E835. As will be explained in more detail in a later chapter, E835 studies charmonium states and needs to have a pbar beam at the resonance energies of these states. This requires the stack to be decelerated, accomplished by bunching the antiprotons at 8 GeV and decreasing the RF frequency synchronously with the decreasing bend field until the desired energy is reached.

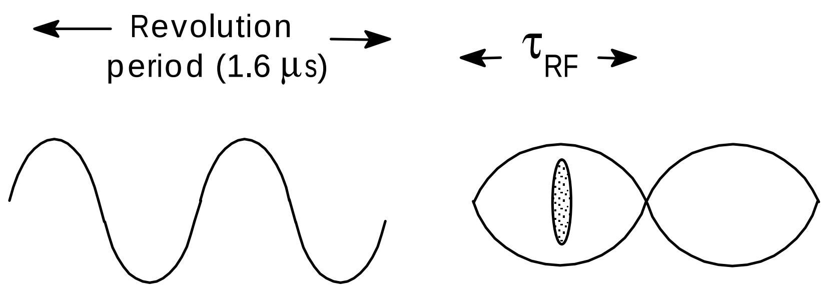

Figure 4.6 ARF-3 structure

The low level amplitude input to ARF-3 comes from either a DAC (A:R3LLAM) or a 164 card (A:R364AM). As with ARF-2, the frequency inputs are provided by a DDS which can be set to a DC level (A:R2FSET) or driven by a 468 card (A:R268FF).

For E835 operation, the amplitude is controlled by the DAC and frequency information is sourced by a 10 MHz digital frequency synthesizer, known as a SCITEQ. The front end computer has special code to control the waveforms of these devices during deceleration.

3. ARF-4

The entire stack is never extracted when antiprotons are transferred to the Main Injector. Rather, a portion of the densest part of the stack is adiabatically captured and accelerated to the extraction orbit. When removing antiprotons from the core, the ARF-4 voltage is slowly increased to capture a portion of the core as defined by the bucket size. The synchronous phase angle is then changed until the bunches are accelerated out of the core to the extraction orbit. The phase angle returns to zero once beam reaches the extraction orbit. The entire process of unstacking pbars takes

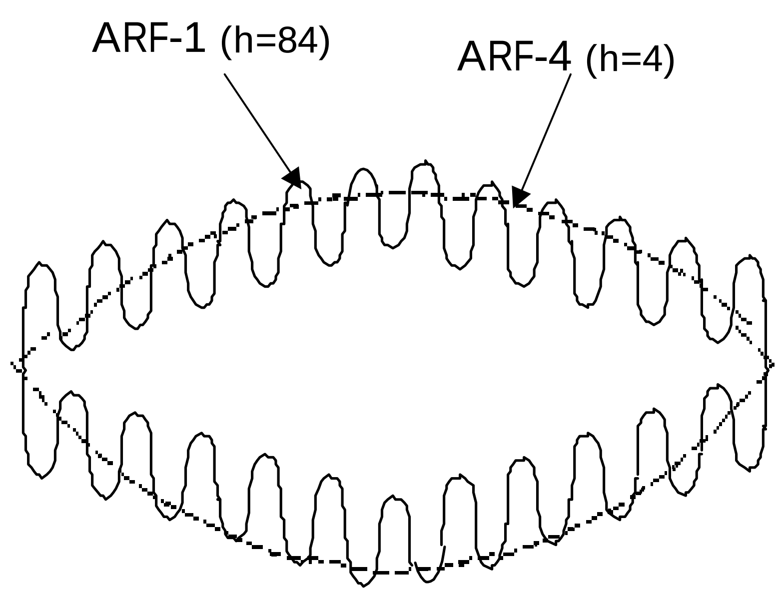

Figure 4.7 Accumulator bunch structure with both ARF-1 and ARF-4 on

approximately 40 seconds.

ARF-4 is a 2.52 MHz h=4 system that was created to allow the transfer of 4 groups of 11 52.8 MHz bunches at a time. Therefore, a typical transfer involves 9 extractions, each one comprised of 4 individual sets of antiproton bunches. ARF-2 and ARF-3 are not involved in the extraction process at all, the ARF-4 voltage is simply turned up to narrow the h=4 bunches. ARF-1 is turned on just prior to extraction to create 11 52.8 MHz bunches within each of the four h=4 bunches. Figure 4.7 shows the bunch structure on each of the h=4 bunches while Figure 4.8 shows a typical ARF-4 waveform during unstacking.

The low level amplitude input to ARF-4 comes from either a DAC (A:R4LLAM) or a 466 card (A:R466A). As with ARF-2 and 3, the frequency inputs are provided by a DDS, which can have a DC value (A:R2FSET) or be driven by a 468 card (A:R268FF). At a later date a different 468 card (A:468F) will be used for the frequency waveform.

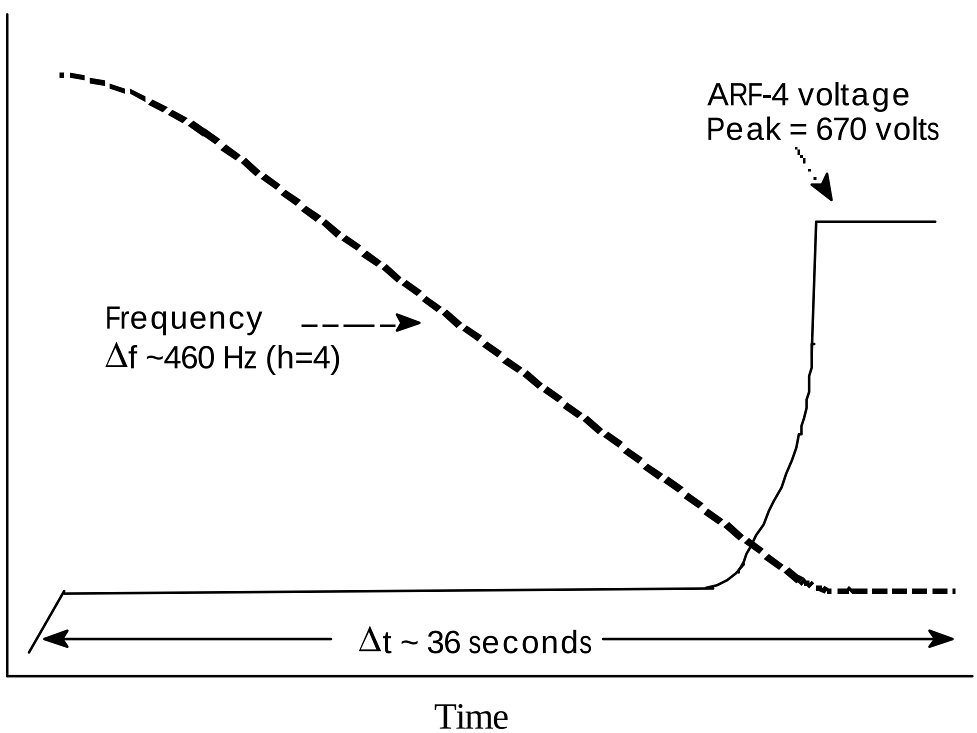

Figure 4.8 ARF-4 waveform for unstacking with a 0.35 eV-s bucket

V. Stochastic cooling

A. Introduction/overview

Beam cooling is a technique whereby the physical size and energy spread of a particle beam circulating in a storage ring is reduced without any accompanying beam loss. The goal is to compress the same number of particles into a beam of smaller size and energy spread, i.e. to increase the particle density. Phase space density can be used as a figure of merit for a particle beam, and cooling increases the density. One may ask how it is possible to increase the phase space density of a particle beam without violating Liouville's Theorem, which states that phase space volume is conserved. The answer is that Liouville's Theorem only applies to "conservative" systems. Cooling, by definition, is not a conservative process. The cooling electronics act on the beam through a feedback loop to alter the beam's momentum or transverse oscillations.

Two types of beam cooling have been demonstrated and used at various laboratories: electron cooling which was pioneered by G. I. Budker, et. al., at Novosibirsk, and stochastic cooling, developed by Simon van der Meer of CERN. Electron cooling gets its name from the fact that an electron beam is used to cool the particles in question. Stochastic cooling is so named because of the stochastic nature of the beam – i.e., particles move at random with respect to one another.

Theoretically, electron cooling works on the principle of a heat exchanger. Two beams travel a certain distance parallel to each other: a 'warm' beam of protons, antiprotons, or heavy ions with relatively large variation in transverse kinetic energy and a 'cold' beam of electrons having much less variation in transverse kinetic energy. Both beams travel at approximately the same velocity and as the beams interact, the transverse kinetic energy of the warmer beam is transferred to the electron beam, which is then collected at the end of the cooling section.

Electron cooling was demonstrated at Fermilab in the early 1980's in a small storage ring known as the Cooling Ring which was located in a blue plywood racetrack-shaped building west of the Linac and Booster. It was on this machine, too, that stochastic cooling was first achieved in the western hemisphere.

During the designing of the Fermilab antiproton source, electron cooling was not the preferred choice due to the lack of proven high current electron sources. Since then, the technology has improved to the point that electron cooling is a viable alternative for future medium-energy storage rings. For that reason, electron cooling is being developed for use in the Recycler Ring. Since the Antiproton Source only employs stochastic cooling at this time, the remainder of this chapter will concentrate on this technique for beam cooling. The stochastic cooling systems used in the Antiproton Source are either betatron or momentum. Betatron, βtron and transverse all refer to systems that reduce betatron oscillations in the horizontal and vertical transverse planes. Similarly, momentum, longitudinal, dp, and Δp are used interchangeably to describe systems that reduce the momentum spread of the beam.

B. Fundamentals

The terms beam temperature and beam cooling have been borrowed from the kinetic theory of gases. Imagine a beam of particles circulating in a storage ring. Particles will oscillate around the beam center in much the same way that particles of a hot gas bounce back and forth between the walls of a container. The larger the amplitude of these oscillations in a beam, the larger the beam size. The mean square velocity spread is used to define the beam temperature in analogy to the temperature of the gas. Beam cooling is desirable for applications such as:

- Providing a low emittance beam to a collider ring in order to maximize collision rate (luminosity).
- Accumulation of rare particles – cooling to make space available so that more beam can be stacked into the same storage ring (e.g. the Accumulator).
- Preservation of beam quality – cooling to compensate for various mechanisms leading to growth of beam size and/or loss of stored particles; Tevatron bunched beam cooling was proposed for this reason, though the Tevatron lattice and bunched beam structure made it difficult to achieve.
- Improvement of interaction rate and resolution-cooling. To provide sharply collimated and highly mono-energetic beams for

precision experiments with colliding beams or beams interacting with targets such as E760 and E835 in the Accumulator.

Consider a single particle circulating in a storage ring as shown in the single particle model depicted in figure 5.1. Assume that the particle has been injected with some error in position and angle with respect to the ideal orbit (the center of the beam pipe). As the focusing system tries to restore the resultant deviation, the particle oscillates around the ideal orbit. These betatron oscillations can be approximated by a purely sinusoidal oscillation. The cooling system is designed to damp the amplitude of this oscillation. A pickup electrode senses the position of the particle on each traversal. The error signal is ideally a short bipolar pulse with an amplitude that is proportional to the particle's deviation at the pickup. The signal is amplified through an octave-band amplifier and applied to kicker electrodes which deflects the particle by an angle proportional to its error.

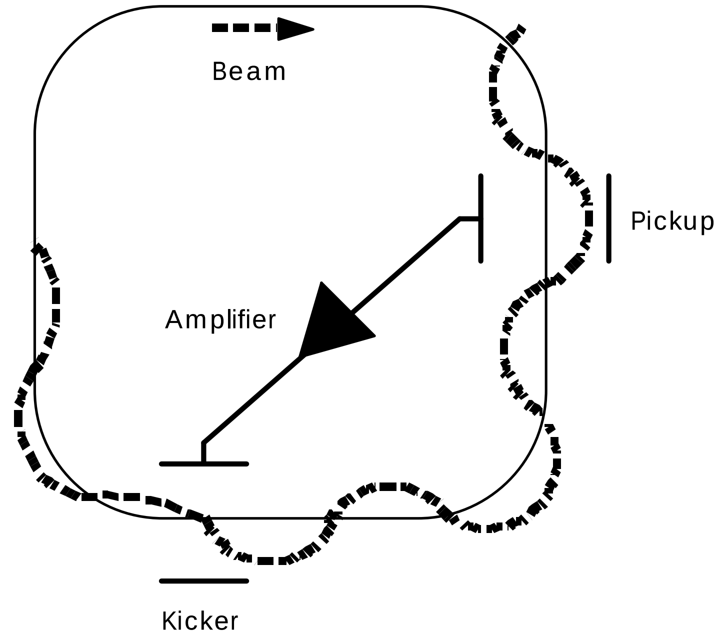

Figure 5.1 One-Particle Model for a Transverse Stochastic Cooling System

Specifically, consider a horizontal beam pickup that consists of two plates (usually parallel) and is sensitive to either horizontal motion or equivalently a dipole oscillation. The pickup is centered on the middle of the beam pipe, with one plate to the left of center and the other to the right. If the particle passes through the pickup off-center, the plate which the particle passes closest to will have a greater current induced on it. If the signals are combined by measuring the difference between them in a so-called ‘delta’ or Δ mode, the output will be a measure of the relative particle position with respect to the center of the beam pipe. Generally, the output of several sets of electrodes are combined in phase to provide a signal of usable amplitude compared to the inherent thermal noise signal. This signal is then amplified and applied with the most optimal averaged phase (timing) to the kickers. The kicker, because of the reciprocity theorem, is a similar arrangement of

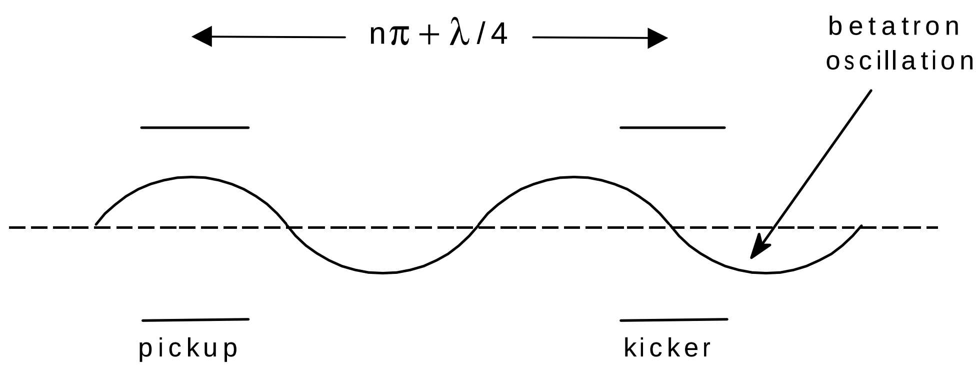

Figure 5.2 Optimum spacing between pickup and kicker

plates on which a transverse electromagnetic field is created which can deflect the particle.

Since the pick-up detects a position error and the kicker provides a corrective angular kick, their distance apart is chosen to correspond to a quarter of a betatron oscillation (plus a multiple of wavelengths if more distance is necessary). As shown in figure 5.2, a particle passing the pick-up at the crest of its oscillation will then cross the kicker with zero position error but with an angular deviation which is proportional to the displacement at the pick-up. Given a perfect kicker response and perfect betatron phasing, the trajectory of the particle would be corrected to that of the central orbit. A particle not crossing the pick-up at the crest of its oscillation would receive only a partial correction and require additional passages to eliminate the oscillation. Cooling systems in fact require many iterations to cool the beam due to the large number of particles involved and the finite bandwidth of the hardware.

There is another important aspect of stochastic cooling that this model may explain: the correction signal has to arrive at the kicker at the same time as the particle for optimum cooling. Since the signal is delayed in the cables and the amplifier, whereas the particle is moving at close to the speed of light, the cooling path has to take a shortcut across the ring to reach the kicker at the correct time. For reasons explained below, applying the correction signal later than on the same revolution when it was created will lead to less efficient cooling or even heating.

Particle beams, of course, are not composed of just a single particle. Rather, a beam is a distribution of particles around the circumference of the storage ring. Each particle oscillates with a unique amplitude and random initial phase and in this model the cooling system acts on a sample of particles within the beam rather than on a single particle. The number of particles in a sample, N_S, is given by:

$$N_s = \frac{N}{(2WT)}$$

where N is the number of particles in the beam, W is the bandwidth of the cooling system, and T is the beam's transit time around the ring. Using one of the Debuncher systems as an example with N = 6 X 10^7 particles, W = 4 GHz (Debuncher systems operate at 4 to 8 GHz), and T = 1.695 μs yields $N_S \approx$ 4,425 particles within each equally spaced sample. Making the bandwidth sufficiently large would permit the single particle model above to be valid, but designing pickups and kickers with good response characteristics is technically extremely difficult.

The cooling process can be looked at as competition between two terms: (a) the coherent term which is generated by the single particle, and, (b) the incoherent term which results from disturbances to the single particle from its fellow sample members through the feedback loop. The coherent signal's contribution to the cooling process is linearly proportional to the system gain while the incoherent heating term is proportional to the square of the system gain. If one plots these two terms as in figure

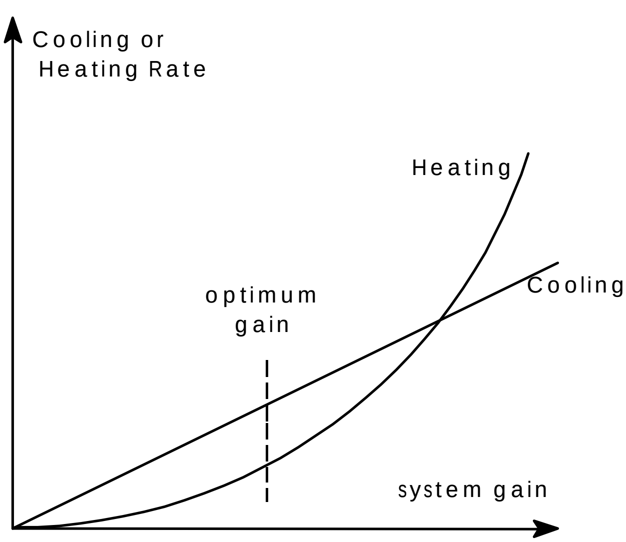

Figure 5.3 Variation of cooling and heating terms with system gain

5.3, it is shown that there is some point at which the cooling term is maximized against the heating term. This is known as the optimum gain of the system. Note that this is usually different from the maximum gain of the system.

Mixing is a term used to represent how completely particles change position with respect to each other. Particles of different momenta "shear" away from each other due to path length differences as they traverse the ring. The stochastic cooling rate is maximized if an independent set of particles constitute each sample upon each revolution. This is sometimes referred to as "good" mixing. The term "stochastic cooling" is derived from the need for a random or stochastic sample of particles passing through the pickup upon each revolution for cooling to work effectively. Partially random samples are produced because each particle is on a slightly different orbit due to the momentum spread of the beam. The lattice parameter known as the "slip factor" also contributes to the rate at which the particle samples are mixed from turn to turn. If the samples contain mostly the same particles from turn to turn, then the cooling rate is decreased.

Although mixing of particles sampled at the pickup is beneficial, no mixing is desired between the pickup and the kicker. This is since the signal obtained at the pickup must be applied at the kicker to the sample creating the signal. Mixing between the pickup and kicker is sometimes referred to as "bad" mixing. An ideal cooling system would have no mixing between the pickup and kicker while having complete mixing between the kicker and the pickup. In reality, the mixing factor present in an accelerator is a compromise between these two extremes. The lattice of the ring in question and the momentum spread of the beam determines the mixing factor.

These factors can be written as an equation for the rate, $^{1}/_{\text{cooling time}}$ or $^{1}/_{\tau_{x^2}}$ (where τ is the cooling time constant), at which a beam is cooled:

$$\frac{1}{t_{x^2}} = \frac{2W}{N}\left[2g\left(1-\tilde{M}^{-2}\right)-g^2\left(M+U\right)\right]$$

where W is the bandwidth of the cooling system, N is the number of particles in the ring, g is the system "gain", or more accurately the number of particles multiplied by the electronic gain, $\tilde{M}$ is the ‘wanted’ mixing factor, M is the ‘unwanted’ mixing factor, and U accounts for random noise.

A list of selected references is included at the end of this chapter which forms the basis for this text and which can provide much more information to the reader on the theoretical aspects of stochastic cooling.

C. Betatron cooling

Betatron or transverse cooling is applied to a beam to reduce its transverse size, i.e. to reduce its horizontal or vertical emittance. The single particle model of cooling described above was that of a simple betatron cooling system. Betatron cooling systems use differential pickups for generating the error signal. In the case of the antiproton source, both pickups and kickers are located in areas of low dispersion. This is so that any particles passing through the pickups off-center will have that position shift due only to transverse oscillations. In a high dispersion region, a particle's position could also be due to differences in momentum, and the resulting kicks could lead to unwanted momentum heating of the beam. A transverse field is applied to the particles by the kickers by applying the error signal to the kicker electrodes in "push-pull" fashion (one kicker plate has the same charge to push the beam, the opposing kicker plate has the opposite charge to pull the beam). Details of the specific transverse systems in the antiproton source are given below.

D. Momentum cooling

Momentum cooling systems reduce the longitudinal energy spread of a beam by accelerating or decelerating particles in the beam distribution towards a central momentum. In a momentum cooling system, the pickup signals are combined in sum mode and similarly, the signal applied to the kicker electrodes is also done in sum mode, providing longitudinal fields to accelerate or decelerate the passing particles.

Momentum cooling is used for several reasons in the Pbar source. Its function in the Debuncher is to further reduce the momentum spread of the beam (bunch rotation is the other mechanism used to reduce the momentum spread in the Debuncher). The stacktail momentum cooling system is used to push the antiprotons deposited by ARF-1 on the edge of the stacktail and decelerate the antiprotons towards the core. The function of the core momentum systems is to maintain a small momentum spread on the particles in the core. This is desirable for two reasons, first to keep particles from striking the Accumulator aperture and second to allow a denser bunch of antiprotons to be extracted during transfers. Accumulator momentum pickups are located in high dispersion areas and are positioned over the beam that is to be cooled (stacktail pickups over the stacktail, core pickups over the core). More details on each Δp system can be found in the following sections.

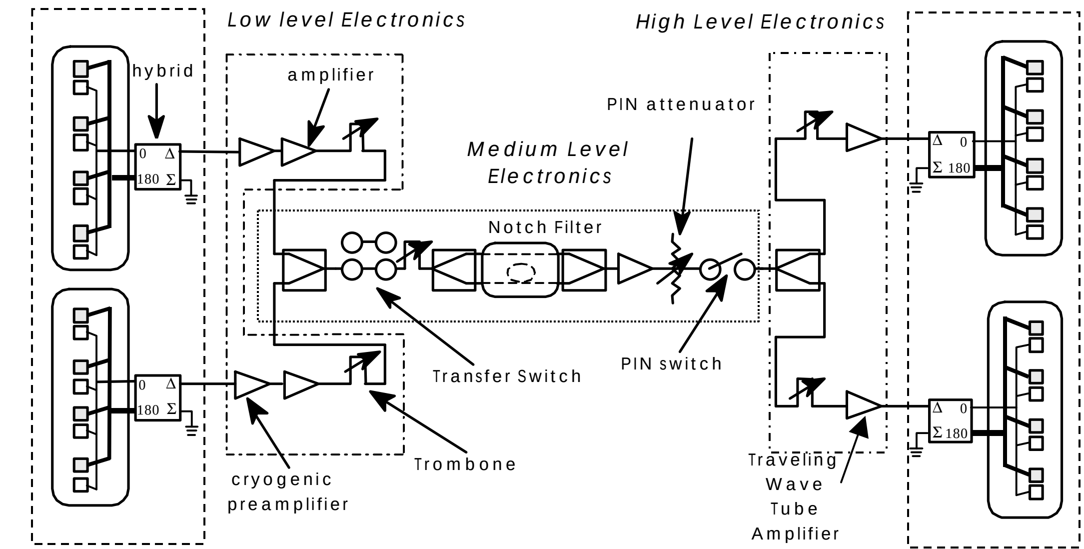

Figure 5.4 Stochastic cooling Basic system schematic

E. Specific systems

The stochastic cooling systems in the Debuncher and Accumulator are described below (use figure 5.4 as a reference). While each of the stochastic cooling systems perform different functions, they each have similar components which will be subdivided into six basic parts for this discussion:

beam pickup electrodes: quarter-wave loop (directional coupler) pickups are contained within a tank assembly which is kept under vacuum. The pickup electrodes are striplines with a terminating resistor on the adjacent grounded walls of the tank. Figure 5.5 illustrates the electric field lines generated by the passage of charged particles. More accurately, each antiproton generates a short pulse in the stripline as it traverses the gaps. The pickup plates form transmission lines with a characteristic impedance. A series of pickup electrodes are housed in a pickup tank. Opposing electrodes

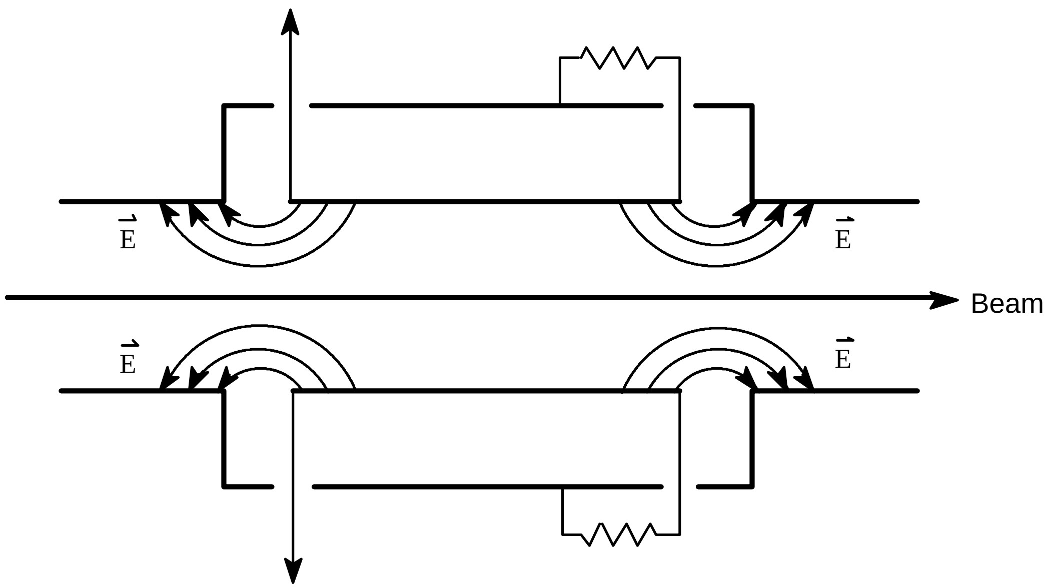

Figure 5.5 Pickup electrode

(top and bottom, left and right, depending on the application) are combined in phase by combiner boards. Sum and difference signals are created by adding or subtracting signals between plates located on opposite sides of the vacuum chamber. Difference signals are used for betatron cooling; sum for momentum cooling. The sum and difference signals are created by passive devices known as hybrids.

low level electronics: the resultant sum and difference information is amplified, then added in phase with information from other cooling tanks, if necessary, by means of mechanical delay lines known as trombones. The first stage of amplification is accomplished by GaAsFET preamplifiers, which in most cases are cryogenically cooled to reduce thermal noise. The Debuncher preamplifiers are cooled to liquid helium temperature, stacktail preamplifiers are cooled to liquid nitrogen temperature. Core systems do not require cryogenic cooling because there is a stronger signal from the beam. The 2-4 GHz core momentum system is the exception, the preamplifiers are cooled to liquid nitrogen temperature. Since the pickup tank is located in A60 along with the stacktail pickup tanks, there was little additional expense required to provide liquid nitrogen to preamplifiers. Ultimately, an amplified signal with a good signal to noise ratio is the input to the next level of the system.

medium level electronics: more amplification is applied and the signal is sent towards the kickers on a single coaxial cable known as a trunk line. Trombones are again used to ensure that the signal arrives at the kickers at the time that the sample of beam producing the signal on the pickups arrives at the kickers. Also included in the medium level electronics are variable PIN (Positive, Intrinsic, Negative: a type of semiconductor) attenuators which permit the gain of the system to be adjusted. Increasing the attenuation (expressed in units of db's) will lower the power output of the system.

Another kind of component found in this level are two varieties of switches. Transfer switches break the continuity between the pick up and kicker in order to make open loop transfer function measurements. The beam is a feedback element in this measurement. PIN switches are means of opening and closing the circuit. PIN switches are used because they are solid state devices that do not have mechanical fatigue problems from frequent cycling. Most PIN switches have gating capability: the switch can be turned on (the circuit is closed), off (the circuit is open), or gated (the switch can be automatically turned on and off via timers). The core systems, for example, are gated during beam transfers so that the cooling is turned off when the clock event which initiates unstacking occurs and is turned back after the transfer has been completed.

An important component of many of the system's medium level circuitry are notch filters. Notch filters act to remove undesired components of the signal from the pickup before being applied to the kicker (in the case of the Accumulator stacktail and Debuncher betatron systems) or to shape the gain profile (as in the case of the Debuncher momentum system). Specific examples will be provided with the description of each cooling system below. Notch filters built for the cooling systems are of the correlator type, which use the constructive and destructive interference of the same signal transmitted over two transmission lines – like an interferometer. The basic components of the filters are a splitter, trombones, phase detectors and a hybrid. The splitter splits the medium level signal between two legs - a 'short' leg which is a straight ahead path for the incoming signal and a 'long' leg which consists of a low loss Bulk Acoustic Wave (BAW) delay line providing approximately one revolution period's worth of delay. Trombones and phase detectors are used to maintain the proper phase relationship between the two legs. A hybrid combines the two legs.

high level electronics: the signal is fanned out to all of the kicker tanks and unraveled in time as appropriate by means of splitters and trombones. Prior to being applied to the kicker electrodes, the signals are further amplified at microwave frequencies through devices known as Traveling Wave Tubes or TWT's. Although part of the high level, the TWT's are treated separately here.

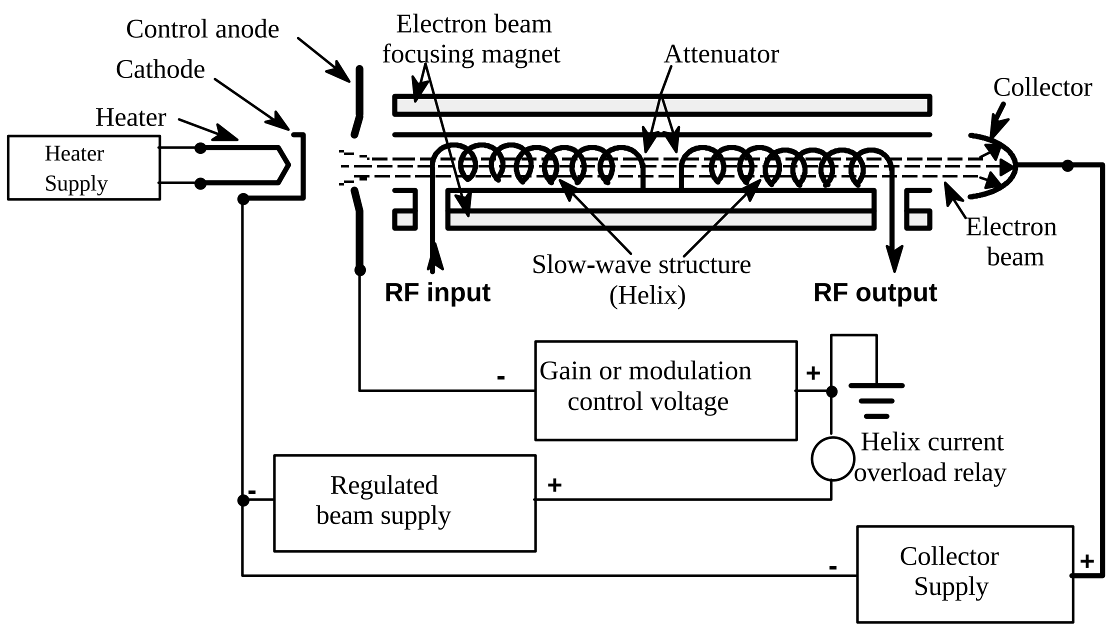

Figure 5.6 Helix type Traveling Wave Tube

Traveling Wave Tube: The TWT is a linear beam tube amplifier that provides 30-60 db of gain over octave bandwidths at microwave frequencies. Power levels of a few watts to thousands of watts are attainable. The TWTs used in the antiproton source for stochastic cooling operate over octave bandwidths of 2-4 GHz and 4-8 GHz. Each has a saturated power level of 200 watts and 40-50 db of gain although they are normally run at 100 watts or less. Refer to figure 5.6, which diagrams a typical TWT, as you read the explanation that follows.

An electron beam is accelerated down the center of a helical 50 Ω transmission line with the helix power supply providing the source of acceleration voltage. The kinetic energy of the electron beam is typically 3-10 keV and beam currents in the 200-500 mA are produced from the TWTs used in the antiproton source. The microwave signal to be amplified is applied to the helical transmission line. Due to the relatively slow velocity of the electron beam, the helical transmission line acts as a "slow wave" structure forcing the propagating microwave signal to match the velocity of the electron beam. Adjustment of the helix supply is necessary to properly match the velocities and optimize tube performance. Propagating in "sync" causes a velocity modulation or bunching of the electron beam resulting in the electron beam imparting some of its energy to the latter part of the slow wave transmission line structure (i.e. gain).

The transmission line is not a resonant structure hence a TWT can have a wide bandwidth of operation. An attenuating material is used to support the helical structure to provide isolation between the input and output (if the attenuation material is omitted, it is a BWO or Backward Wave Oscillator). The entire slow wave structure, electron source (cathode) and collector are housed in a sealed stainless steel vacuum envelope. The beam is confined within the helix with permanent magnet focusing. Some higher power TWTs use powered solenoidal magnets, but those used in the antiproton source use rare earth magnets. The efficiency of TWTs is typically below 20% and those used for stochastic cooling in the antiproton source are about 10% efficient. The excess beam energy ends up in the collector. To improve efficiency, several stages of collector may be employed. While the stochastic cooling TWTs typically have one or two stages, some may have up to 4 collectors to improve efficiency. An anode may be added to the TWT to provide modulation or gain control. Only the 2-4 GHz TWTs at Fermilab have a modulation anode.

The power supplies for a TWT must be very well regulated to produce a stable electron beam. The propagation time through a TWT is approximately 10-15 nanoseconds while the stochastic cooling systems require timing precision to a few picoseconds. Voltage ripple of just a fraction of a percent is sufficient to cause enough propagation velocity variation in the electron beam to cause system timing problems.

kicker electrodes: physically the kicker electrodes are identical to their pickup counterparts. Each loop is terminated with a resistor and is rated to handle up to 10 Watts of microwave power. The stacktail and core kicker tanks in straight section 30 are outfitted with a design of array referred to as a planar loop as opposed to the original three-dimensional microstrip kicker design. Planar loops are made on printed circuit boards and are considered superior in terms of ease of fabrication and improved mechanical tolerances.

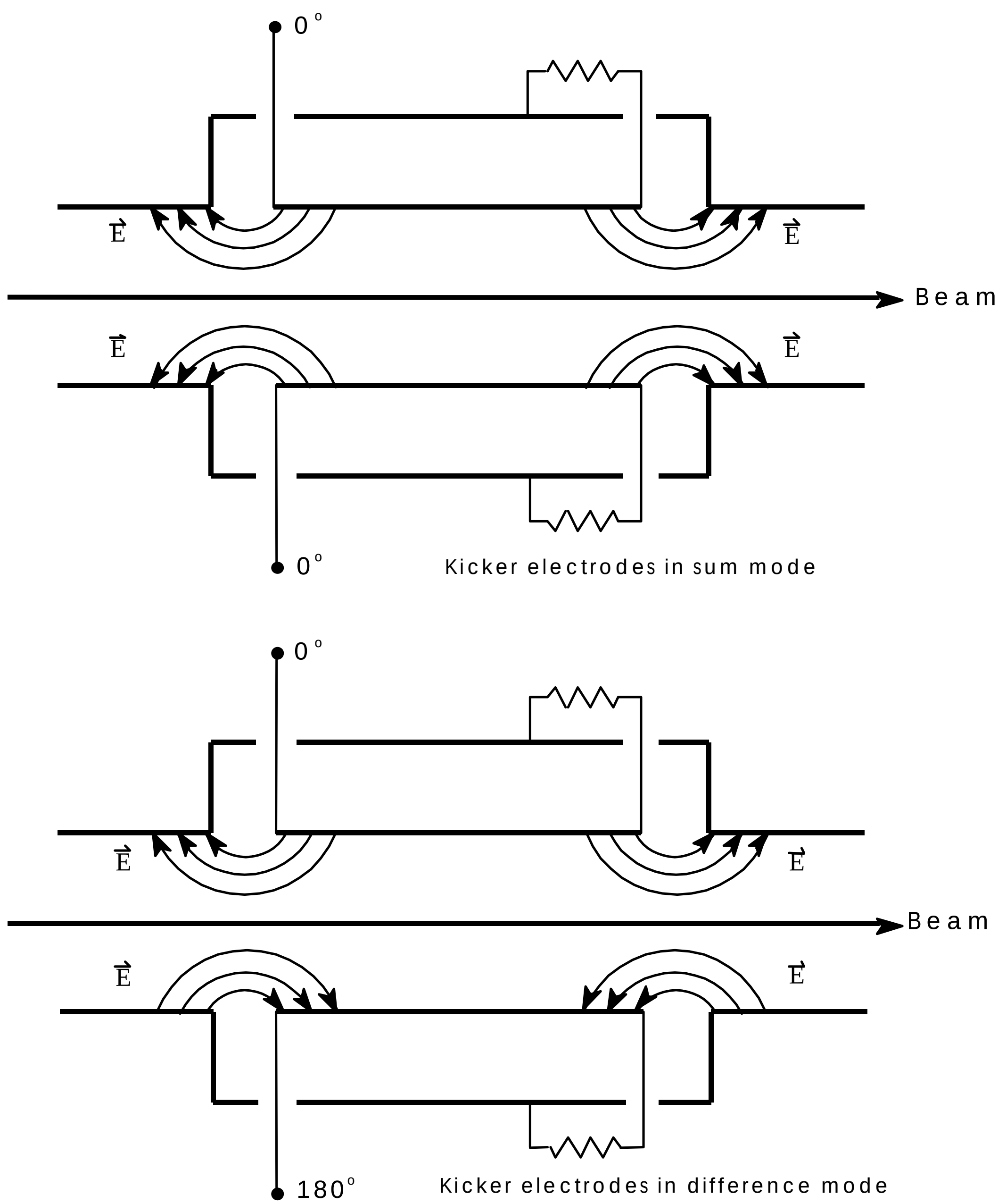

Figure 5.7 Kicker electrodes in sum and difference mode

The kicker arrays and terminating resistors are cooled with water provided by a closed-loop system. Make-up water to the system comes from Pbar 95 LCW, but there are no deionizing cartridges used to preserve the low conductivity. The cooling water is usually referred to as "clean" water, and has excess heat removed by heat exchanging with 55 degree chilled water. Chilled water was originally used for cooling the tanks, but proved to be too dirty causing clogged flow turbines and reduced cooling efficiency

Although kicker electrodes for transverse and longitudinal cooling systems are physically the same, there is a difference in how the correction signals are applied to them. Simplified diagrams of kickers in both sum (longitudinal) and difference (transverse) modes are illustrated in Figure 5.7. As with pickup electrodes, excitation of the beam takes place at the gaps between the pickup and grounded wall. Again referring to Figure 5.7 note that in sum mode the signals applied to the kicker electrodes are in phase with each other. When in sum mode the electric fields are oriented so that a longitudinal kick is applied to the beam. In difference mode the signals are 180° out of phase with respect to each other and the electric fields result in a transverse kick to off-center particles.

System	Debuncher Horizontal	Debuncher Vertical	Debuncher Momentum
Pickup location	D10	D10	D10
Kicker Location	D30	D30	D30
# of pickup pairs	128 4 tanks with 32 each	128 4 tanks with 32 each	256 all of the H&V pickups
Bandwidth	4-8 GHz	4-8 GHz	4-8 GHz
# of TWT's	16	16	32
# of kicker pairs	128	128	256
typical operating power	1,000 watts	1,000 watts	1,500 watts

Table 1 Debuncher Cooling Systems

1. Debuncher Betatron

The Debuncher Betatron systems reduce the transverse emittances of beam in the Debuncher so that it will fit into the Accumulator. Each system presently reduces the emittance from 17 pi-mm-mrad to 4 pi-mm-mrad in 1.5 seconds. The bandwidth of these cooling systems is 4-8 GHz. A total of 128 pairs of pickup electrodes are spaced over six vacuum tanks located in straight section D10 for each system. Because the pbar intensity in the Debuncher averages only 6-9x10^7 particles, the coherent signal derived from the beam needs to be maximized. In addition to summing the signal from four tanks of pickups, the electrodes as well as the preamplifiers are cooled with liquid helium. This serves to reduce the thermal noise, which would contribute to the heating term. Unwanted signals are also removed by the use of correlator Bulk Acoustic Wave (BAW) notch filters. These filters notch out unwanted thermal noise at harmonics of the revolution frequency and between betatron sidebands, leaving only the signals from the betatron sidebands as signals, which are amplified by the TWTs and applied to the kickers. By increasing the signal to noise ratio, less TWT power is produced as noise that would heat the beam leaving more power to cool the beam.

The four kicker tanks are located in straight section D30 (see figure 5-8). Due to the length of the pickup and kicker arrays and the need to keep the proper phase advance between the pickups and kickers, the 4 tanks are separated by 180° of betatron phase advance and combined with a 180° hybrid. The 128 kicker electrodes in each plane are powered by 16 TWTs at an average total power of about 1000 Watts per plane. The LCW-cooled TWTs are mounted directly on the kicker tanks.

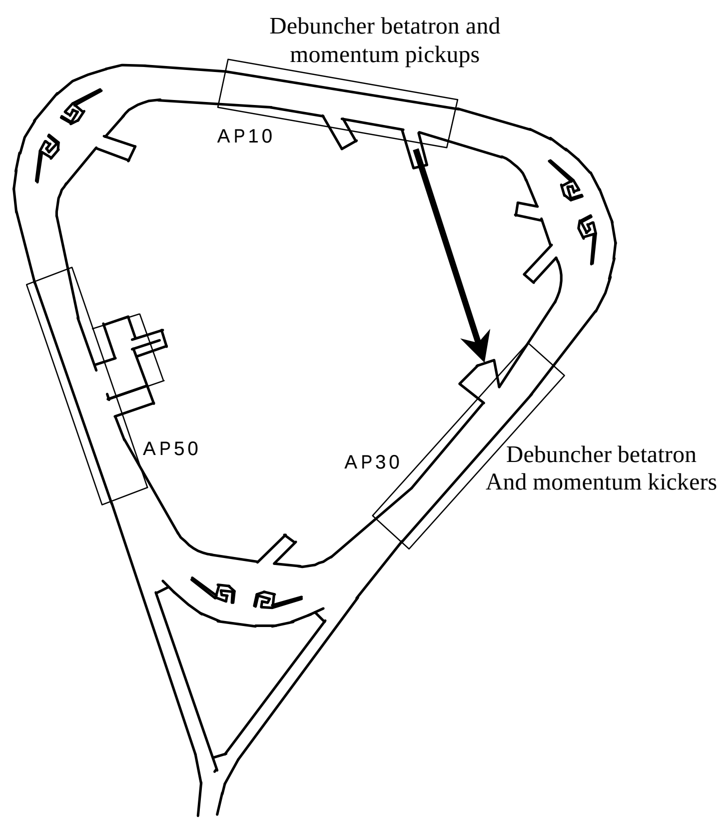

Figure 5.8 Location of Debuncher stochastic cooling systems

2. Debuncher Momentum

Antiprotons that circulate in the Debuncher have their momentum spread further reduced after bunch rotation and adiabatic debunching by means of a momentum cooling system. This cooling system was added in 1989 and uses the same pickup and kicker electrodes as those in the Debuncher betatron systems. Instead of using the signals from the pickups in the difference mode, however, the sum signal is gathered. Similarly, the signal applied by the kickers to the beam is in the sum mode. The frequency range of this system is 4-8 GHz. This system currently reduces the Debuncher $\Delta p/p$ (momentum spread) from ~ 0.30% to < 0.17% in 2.4 seconds

All of the Debuncher transverse pickup and kicker electrodes are used for the momentum system – the kickers are driven with both momentum and transverse signals. 32 TWTs dedicated only to momentum cooling, again mounted on the kicker tanks, provide a nominal 1,500 watts of longitudinal cooling. This system also has a notch filter that provides the gain shaping necessary to do momentum cooling.

System	Stack Tail Δp	Core 2-4 βtron	Core 4-8 βtron	Core 2-4 Δp	Core 4-8 Δp
Pickup location	A60	A10	A10	A60	A20
Kicker Location	A30	A30	A30	A30	A50
# of pickup sets	256 at +15.7 MeV (2 tanks with 128 each) 48 at –3.8 MeV 16 at –22.7 MeV	16 planar pairs each plane	32 planar pairs each plane	16 at core orbit 16 at central orbit	32
Bandwidth	2-4 GHz	2-4 GHz	4-8 GHz	2-4 GHz	4-8 GHz
# of TWT's	32 sum 4 delta	1 horizontal 1 vertical	1 horizontal 1 vertical	1	2
# of kicker pairs	256 with 64 delta kicker pairs (half vertically half horizontally oriented)	16 each plane	32 each plane	32	64
typical operating power	1,000 watts	50 watts each plane	20 watts each plane	40 watts	0-10 watts

Table 2 Accumulator Cooling Systems

3. Accumulator Stack Tail Momentum

After antiprotons have been injected into the Accumulator, the particles must be decelerated roughly 150 MeV to reach the core. The first 60 MeV of deceleration is handled by ARF-1 while the final 90 MeV is accomplished by the 2-4 GHz stacktail momentum system. Because an RF bucket displaces beam that it passes through, it was not possible to use an RF system to decelerate beam the full 150 MeV to the core.

All of the stacktail pickups are located in the A60 high dispersion region and are subdivided into three separate arrays called the +15.7 MeV (leg 1), –3.8 MeV (leg 2) and –22.9 MeV (leg 3 or compensation leg) pickups. Figure 5.9 shows the relative positions of the stacktail and core momentum pickups.

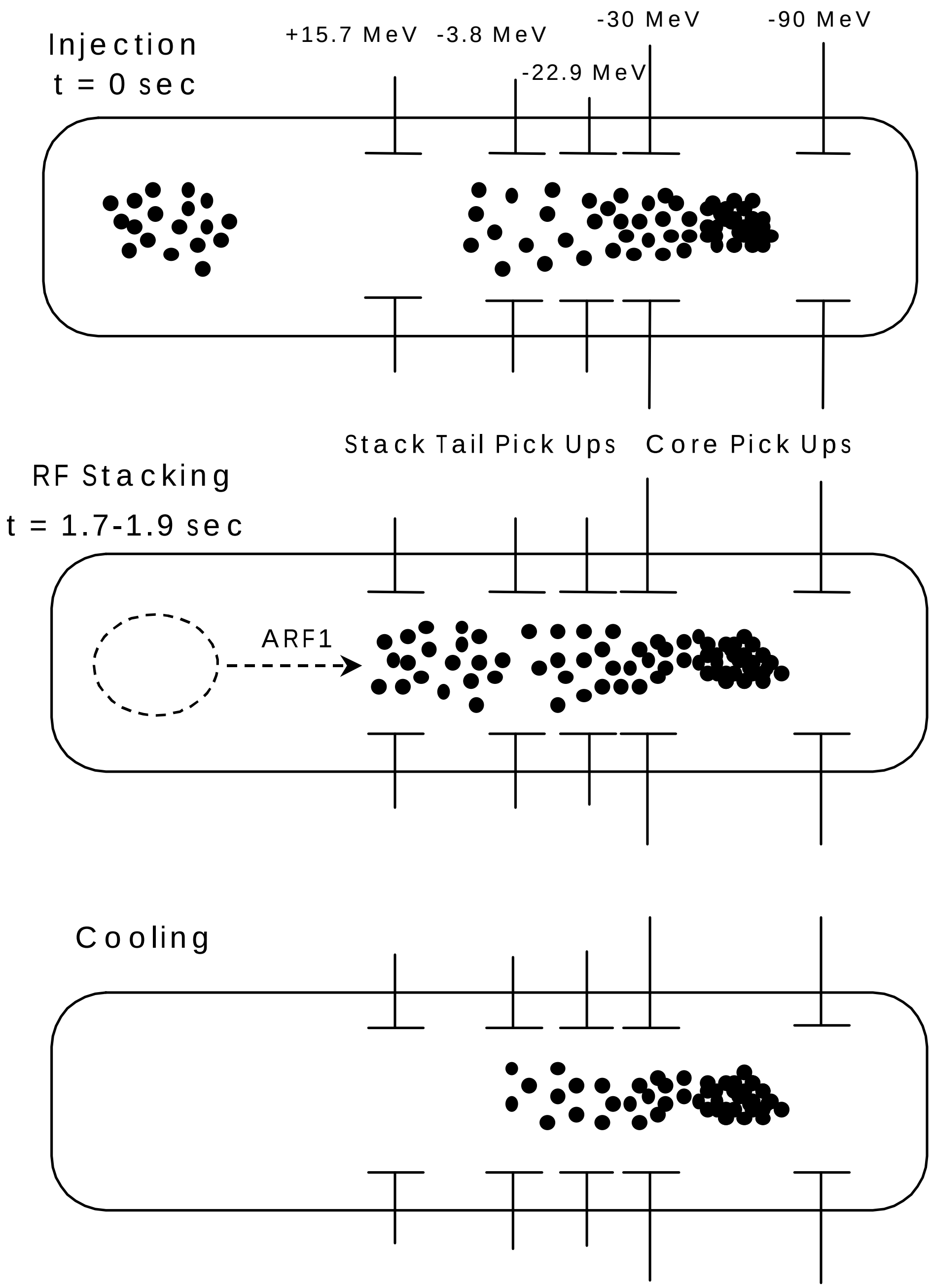

Figure 5.9 Stacktail and core momentum pickup location

The pickup names identify the part of the stacktail for which the particular pickup array is most sensitive relative to the central orbit of the Accumulator. The stacktail extends from about +30 MeV where ARF1 deposits beam to the edge of the core at about -30 MeV. The +15.7 MeV pickups are most sensitive to beam that is 15.7 MeV higher in energy than beam located on the central orbit. The shift in position at the pickup is due to the dispersion at that location. A difference in energy results in a primarily horizontal position shift (there is very little vertical dispersion in the Accumulator). A notable difference in the three arrays is in the number of pickup elements each one contains. The +15.7 MeV pickups are made up of 256 individual pickup electrode pairs divided evenly between two different tanks. The –3.8 MeV pickups, made up of 48 electrodes, and the –22.9 MeV pickups having only 16 electrodes, are located inside another tank. Figure 5.10 shows the location of the pickup tanks in the A60 straight and the kickers in the A30 straight section.

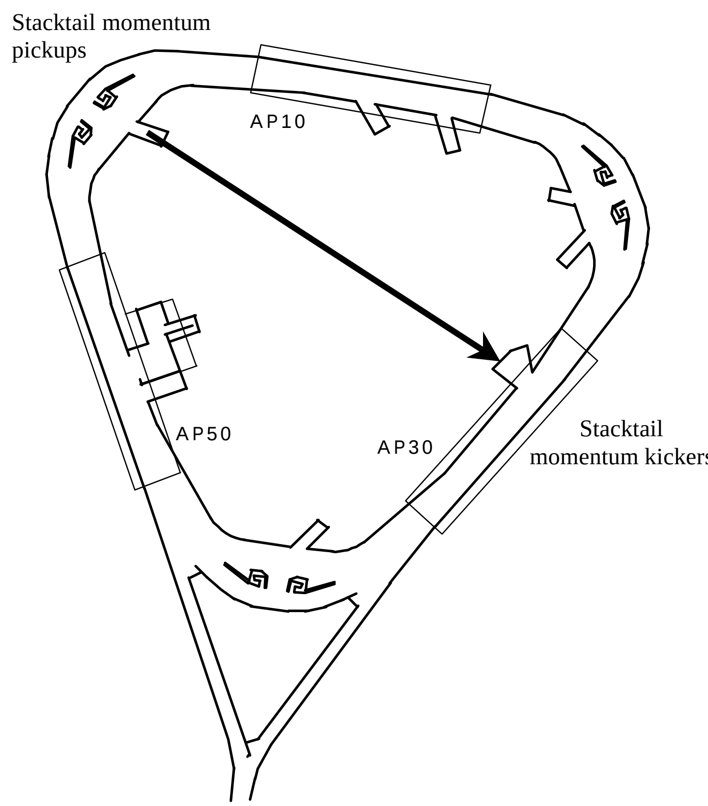

Figure 5.10 Location of Accumulator stacktail momentum cooling system

To understand why there are so many pickup electrodes at +15.7 MeV and so few at –22.9 MeV, consider how beam is distributed in the stacktail. At the deposition orbit, the point where ARF-1 drops off the beam, there is a relatively small amount of beam for the +15.7 MeV electrodes to detect. For the stacktail system to work effectively, a certain amount of beam signal must be detected above the background noise. Thermal noise from the pickups is reduced by cooling parts of the pickup assemblies to liquid nitrogen temperature. To achieve the proper amount of beam signal from the +15.7 MeV array, it is necessary to have a large number of pickups. The –22.9 MeV pickups, on the other hand, are located much closer to the core where there is considerably more beam. Sixteen electrodes are adequate to produce a reasonable signal to noise ratio.

The signals coming from the pickup arrays are manipulated by the stacktail electronics and provide the phase and gain characteristics necessary to effectively momentum cool the beam in the stacktail while minimizing effects on beam in the core. The system gain changes nearly exponentially across the stacktail, and is highest where ARF-1 drops beam off and lowest at the edge of the core. Because of this, the high energy beam arriving at the edge of the stacktail moves very rapidly away from the deposition orbit. It is important for the stacktail system to have this feature since any beam remaining near the deposition orbit will be RF displaced into the injection kicker shutter when ARF-1 pulses on the next stacking cycle. Low energy beam on the core side of the stacktail moves very slowly and tends to "pile up" against the core, giving the stacktail its characteristic shape which is

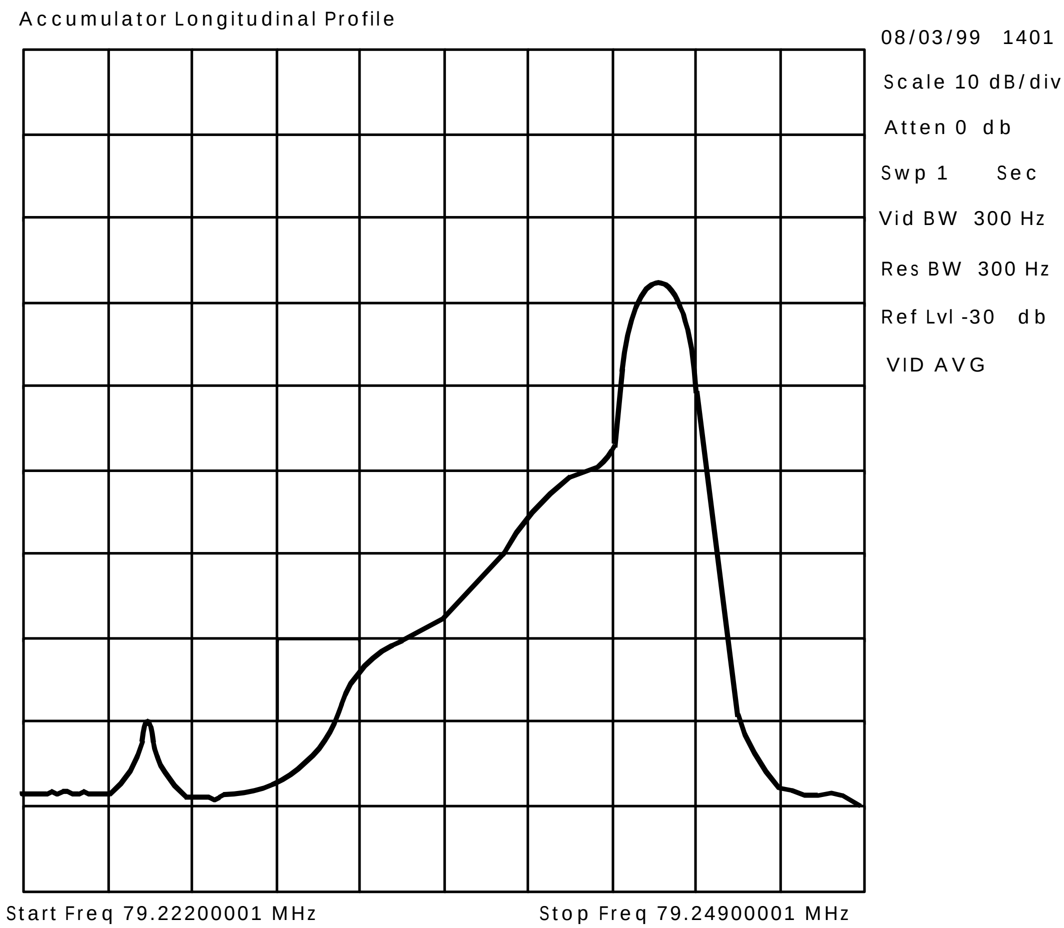

Figure 5.11 Accumulator spectrum analyzer display

illustrated in figure 5.11.

Transverse kicks induced by the stacktail momentum system, mostly due to imperfect hybrids and kicker misalignment, lead to betatron heating of the beam in the stacktail and core. This is partially overcome in the stacktail system by applying a small part of the signal from 64 sets of the kicker electrodes in the difference or delta mode (recall that momentum pickups and kickers are normally in the sum mode). The first and last kicker tanks in the A30 straight section are stacktail tanks used as "delta kickers". These tanks were selected because they are nearly 90° out of betatron phase with each other. Half of all of the stacktail momentum kicker electrodes are oriented horizontally and the other half are oriented vertically. Since the signal is applied in sum to each electrode pair, the particles passing between the plates see a longitudinal field. The delta kickers have the difference signal applied, resulting in a transverse kick to the beam. The delay and attenuation values for the delta kickers are calculated using network analyzer beam measurements to offset the heating induced by their longitudinal counterparts.

4. Core Momentum

The Core momentum cooling systems keep the antiproton core contained by decelerating high energy particles and accelerating low energy particles. There are two core momentum systems currently in use. The original 2-4 GHz system, which has its pickup tank in the A60 high dispersion straight section and kickers in the A30 area (see figure

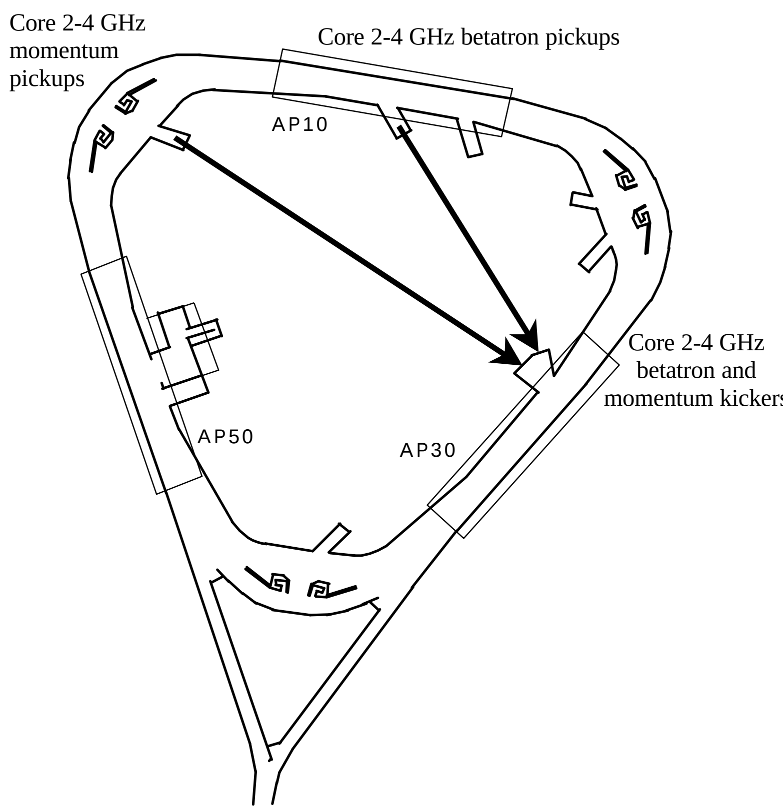

Figure 5.12 Location of Accumulator core 2-4 GHz stochastic cooling systems

5.12), and the 4-8 GHz system added in 1989 which includes a pickup tank in the A20 section and a kicker tank in A50 (see figure 5.13). The 4-8 GHz system was first used by E760 because of its ability to provide a smaller momentum spread and decreased cooling time. Another important advantage of this system for E760 (and now E835) was that the pickup arrays could be remotely moved so they could be centered on beam on the central orbit. During data taking, most experiments maintain the stack at the central orbit of the Accumulator rather than at the low-energy side of the Accumulator as is the case during stacking operation.

The 4-8 GHz core momentum system was later pressed into service during the 1992-93 Collider run to provide a denser core from which to unstack antiproton bunches. Typically the 4-8 GHz core momentum system was kept off during stacking and the beginning of the shot set-up. The system was then turned on approximately midway during the set-up to provide time for the core to narrow and then stabilize with this system on. The two core momentum systems are stand-alone systems, so it is possible for them to cool the core to different momenta. The 4-8 GHz core momentum system is more efficient than the 2-4 GHz core momentum system (at the expense of the momentum range over which it can cool) because of the greater bandwidth of the 4-8 GHz system. Normally the pickups of the 4-8 GHz system are positioned so that both systems are cooling to the same revolution frequency (at this time only the 4-8 GHz pickup

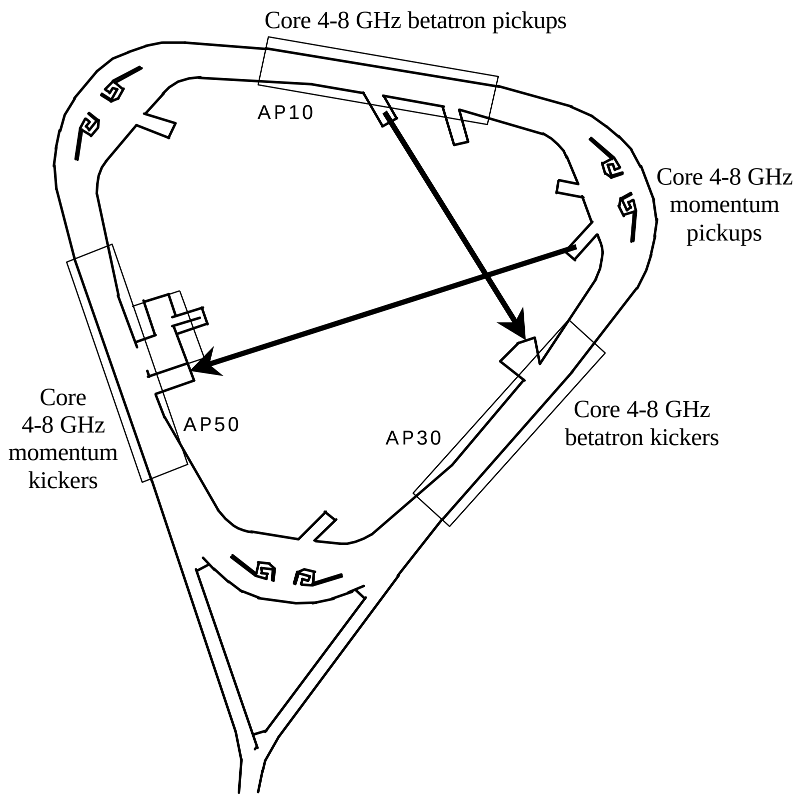

Figure 5.13 Location of Accumulator core 4-8 GHz stochastic cooling systems

arrays can be moved). With the upgrade of the stacktail momentum system to 2-4 GHz, the 4-8 GHz core momentum system will carry most of the cooling load in the future. The 2-4 GHz core momentum system has not been decommissioned, however.

5. Core Betatron

There are both 2-4 GHz and 4-8 GHz transverse cooling systems made up of a horizontal and vertical system each. These systems exist to control the transverse emittances of particles in the core. Pickup tanks are located in the A10 low dispersion straight section, an area where any sensed position error will be due to transverse rather than longitudinal (momentum) oscillations. The kickers are in the A30 straight section.

Originally horizontal and vertical core betatron cooling systems were operated in the 2-4 GHz bandwidth. Both systems were then upgraded to operate at 4-8 GHz by replacing the pickup arrays (which were also an improved planar loop design) and installing new kicker tanks. Although the 4-8 GHz transverse systems cooled the core more efficiently, they did not extend their domain into the edge of the stacktail as the 2-4 GHz systems had. Also, the response of the 4-8 GHz systems dropped off more rapidly at higher frequencies than anticipated. The effective bandwidth of the 4-8 GHz systems was only slightly better than the 2-4 GHz systems (not the expected doubling). In the spring of 1995 the 2-4 GHz systems were recommissioned by replacing half of the planar array pickups that had formerly been used by the 4-8 GHz systems and using the existing kicker tanks in A30 (the 2-4 GHz core betatron and core momentum systems share the same kickers). Normally the 2-4 GHz and 4-8 GHz transverse systems are run simultaneously. The plan is to eventually build equalizers for the 4-8 GHz systems to compensate for the loss of response in the higher frequencies.

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VI. Transport Lines

A. Introduction

Four beam transport lines are used in the Antiproton source to connect the Debuncher and Accumulator, and to provide a path to and from the Main Injector beamlines:

- AP1 transports 120 GeV protons extracted from the Main Injector to the pbar production target via the P1 and P2 lines. When oriented at 8 GeV, AP-1 delivers antiprotons extracted from the Accumulator towards the Main Injector. Protons can also be "reverse injected" from the Main Injector to the Accumulator for shot tune-up or studies.

- AP2 transports 8 GeV antiprotons from the target station and injects them into the Debuncher ring. Protons can be reverse injected from the Debuncher into the AP2 line for studies. On infrequent occasions magnet polarities are reversed in the AP-2 line and the target and collection lens removed to allow 8-GeV protons from the Main Injector to be transported to the Debuncher.

- AP3, in conjunction with AP1, carries extracted 8 GeV antiprotons from the Accumulator to the Main Injector and delivers 8 GeV "reverse" protons from the Main Injector to the Accumulator.

- The D to A line transfers antiprotons between the Debuncher and Accumulator. Protons that have been reverse injected into the Accumulator can also be transferred into the Debuncher for studies.

Maps of the beamlines can be found in the Appendix at the end of this section. Information on electrical, cooling water and vacuum systems are consistent with those found in the rings, details can be found in the Utilities chapter of this book. The Diagnostics chapter of this book contains information about Beam Position Monitors (BPM's), Beam Loss Monitors

Beam line	Dipoles		Quads		Trims	
	Power supplies	Magnets	Power Supplies	Magnets	Power Supplies	Magnets
AP1 120 GeV	M:H10*	PB*	M:Q10*	PQ*	M:HT10*	PQ*-HT
AP1 8 GeV	M:H20*	PB*	M:Q20*	PQ*	M:HT10*	PQ*-HT
AP2	D:H7**	IB*	D:Q7**	IQ**	D:HT7**	IQ**-HT
D to A	D:H8**	TB*	D:Q8**	TQ*	D:HT8**	TQ*-HT
AP3	D:H9**	EB*	D:Q9**	EQ**	D:HT9**	EQ**-HT

Table 1 Naming conventions

(BLM's) Secondary Emission Monitors (SEM's) and other diagnostics found in the transport lines.

B. Naming Conventions

The naming convention used in the transport lines can be confusing, as there are both magnet names and power supply names. Magnets are generally identified by their installation names since the power supplies are often connected to multiple loads. Tables 1 summarizes magnet and power supply names for the beamlines.

The leading letter in the magnet names represents which beamline it's a part of; for AP1 magnets the "P" is for "Proton", in AP2 the "I" is for "Injection", in the D to A line the "T" is for "Transfer" and in AP3 the "E" is for "Extraction". The second letter is somewhat intuitive, "B" is for "bend" (dipole), "Q" is for "quad". Trims are identified with a hyphenated extension, HT (VT) for a horizontal (vertical) trim. Dipoles are assumed to be horizontal unless otherwise indicated, e.g. IB1 is a horizontal dipole while IBV1 is a vertical dipole. Note that AP1 line trims have a single power supply that can be used for either 8 GeV or 120 GeV operation.

C. Kickers and septa

Beam transfer to and from the Pbar rings is accomplished with kicker and septum pairs. An injection septum bends the beam from a transport line into an accelerator and an injection kicker deflects the beam on to the closed orbit. An extraction kicker deflects beam from the closed orbit into the field region of a septum, which in turn bends the beam into a transport line. There are two styles of kickers in the antiproton source, an Accumulator style and a

Debuncher style that both produce magnetic fields of approximately 500 Gauss. Septa also come in two different styles, although all but the Accumulator extraction Lambertson are made up of a single-turn design.

1. Kickers

The Debuncher injection and extraction kickers are ferrite single-turn transmission line pulsed magnets that are similar in design to those found in the Booster, Main Ring and Tevatron. The 200 nanosecond fall time for the injection kicker and rise time for the extraction kicker required some

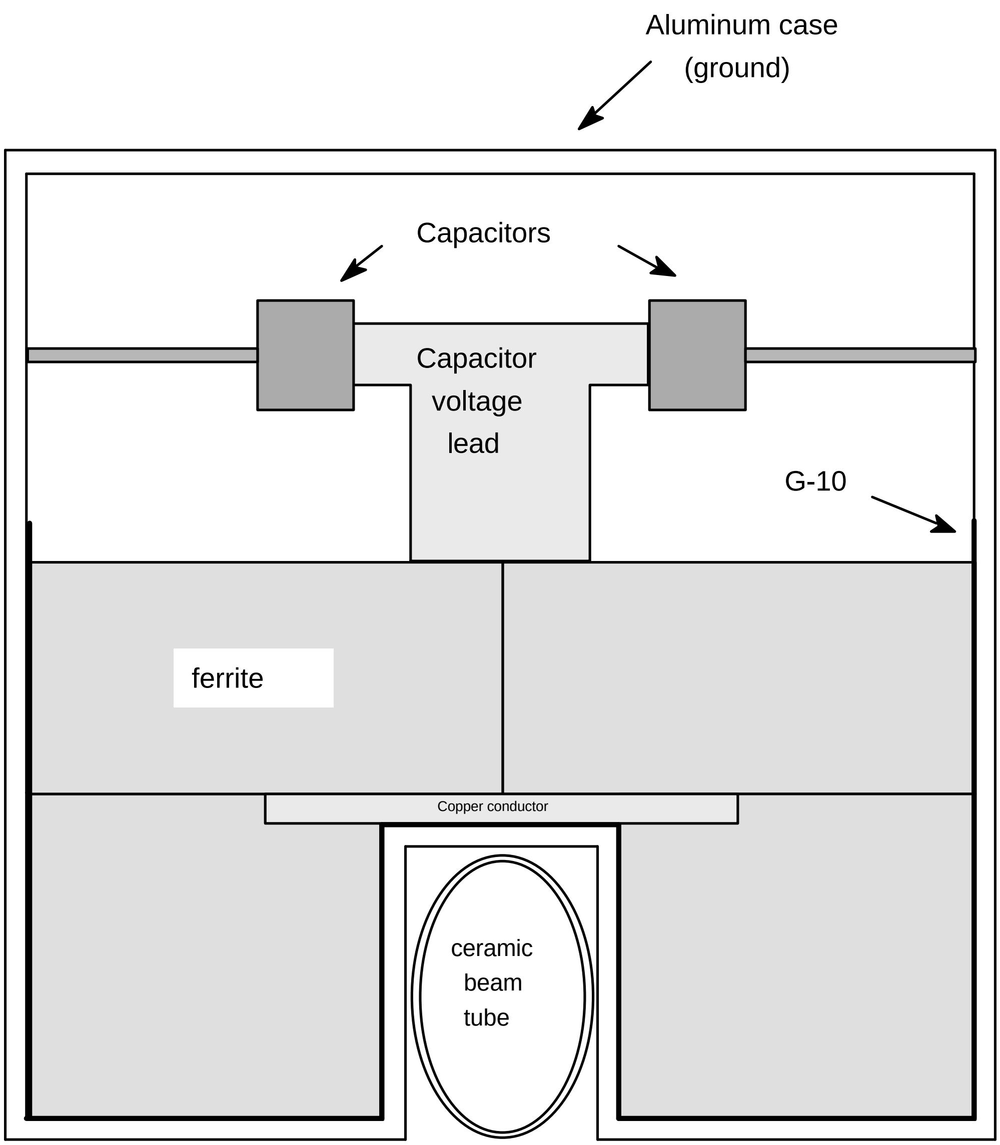

Figure 6.1 End view of Debuncher injection kicker

modifications from kickers previously designed.

Debuncher kickers are made up of three separate modules to limit propagation delay. Figure 6.1 is an end view of the Debuncher injection kicker, use it as a reference in the following description. Each module is about a meter long and is made up of a series of 48 sets of 4 ferrite blocks about 1.8 cm thick stacked around a copper conductor. 12 pairs of capacitors are connected on one end to the central copper conductor that carries the current. The other end is connected to the aluminum case, which is grounded. The module case does not contain the beam tube, which is an external elliptical ceramic chamber 5.7 cm. x 4.1 cm. The module has a "c" shape that surrounds the beam tube on three sides, replacing Debuncher kicker modules doesn't require vacuum to be broken. With the central conductor and ferrites providing the inductance and the capacitors providing the capacitance to the circuit, the magnet electrically looks like a 10Ω transmission line. The ferrites, which are at high voltage like the conductor, are insulated from the outer case with G-10. The capacitors and capacitor leads are potted with an insulating rubber compound.

The Accumulator injection and extraction kickers bear little physical resemblance to their Debuncher counterparts although they are similar electrically. Many of the design considerations were driven by the need for a shutter to shield the antiproton core from the kicker pulse. The shutter is a plate of aluminum 5 mm thick and 3 m long. Three titanium arms "rock" the shutter in to and out of place and are driven through linkage by a DC stepping motor.

The Accumulator kickers have a cylindrical conductor surrounded by "c" shaped ferrites. The ferrites are specially prepared and handled to minimize outgassing. Capacitance in the kicker circuit is provided by distributing parallel plate capacitors along the length of the magnet. High voltage plates are attached to the center conductor and ground plates are located between the high voltage plates. The capacitors make use of an alumina ceramic as a dielectric as well as for various insulating components.

The A20 straight section contains both Accumulator kickers. The kickers are housed in tanks that are similar in appearance to stacktail pickup tanks. Large high voltage cables feeding into the kicker tanks distinguishes them from stochastic cooling tanks. Due to the ultra high vacuum requirements of

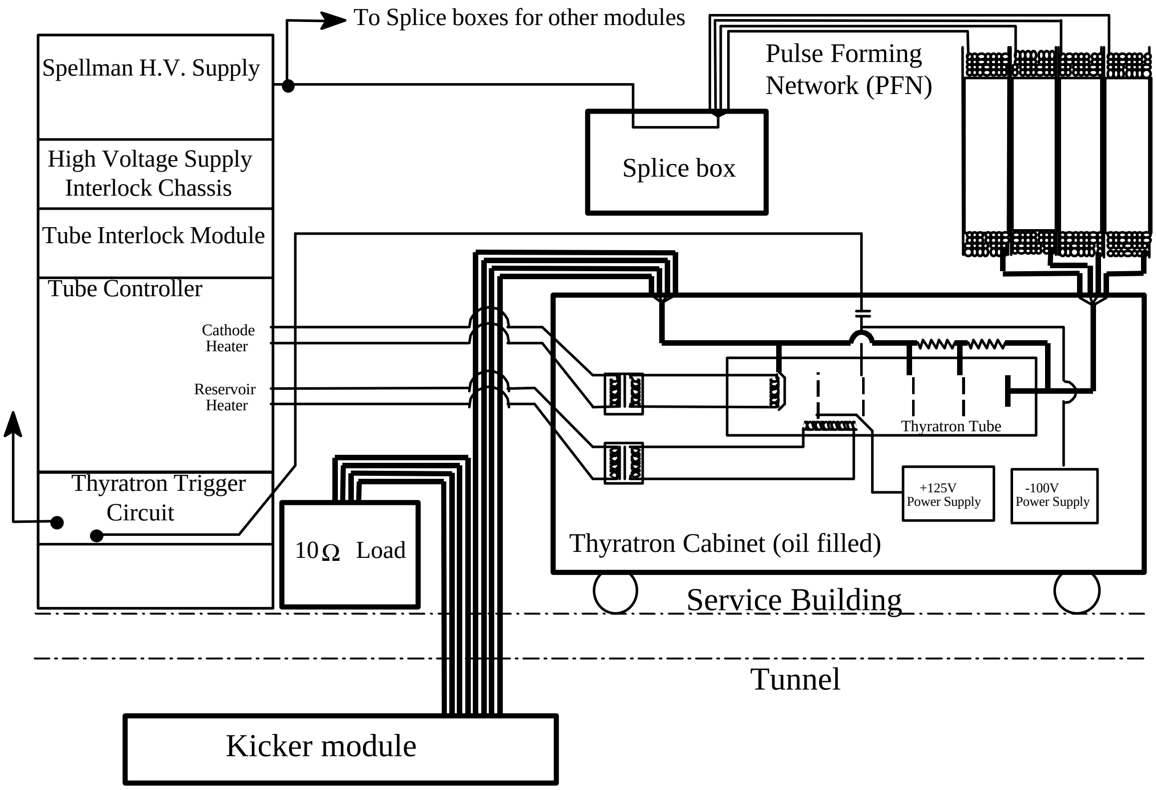

Figure 6.2 Kicker power supply

the Accumulator, the magnets and tanks are baked out along with other components during start-ups.

Power supplies are virtually the same for both Accumulator and Debuncher kickers. Figure 6.2 diagrams a typical kicker power supply and associated components. A hydrogen thyratron switch tube is used as a high voltage switch to allow the electrical current to pulse through the kicker. High voltage cable is coiled on large aluminum frames to provide a Pulse Forming Network (PFN) that helps form the shape and duration of the kicker pulse. During a typical stacking cycle the PFN's are charged up over about .5 sec to around 60 kV by a Spellman high voltage power supply. A LeCroy timing module provides a pulse to a kicker trigger module at the appropriate time which in turn "fires" the thyratron tube. This closes the circuit and allows a current pulse to pass through the kicker magnet to a 10Ω load. The thyratron tube is housed in an oil-filled cabinet located in the service building. The 10Ω load and PFN's are also located in the service building.

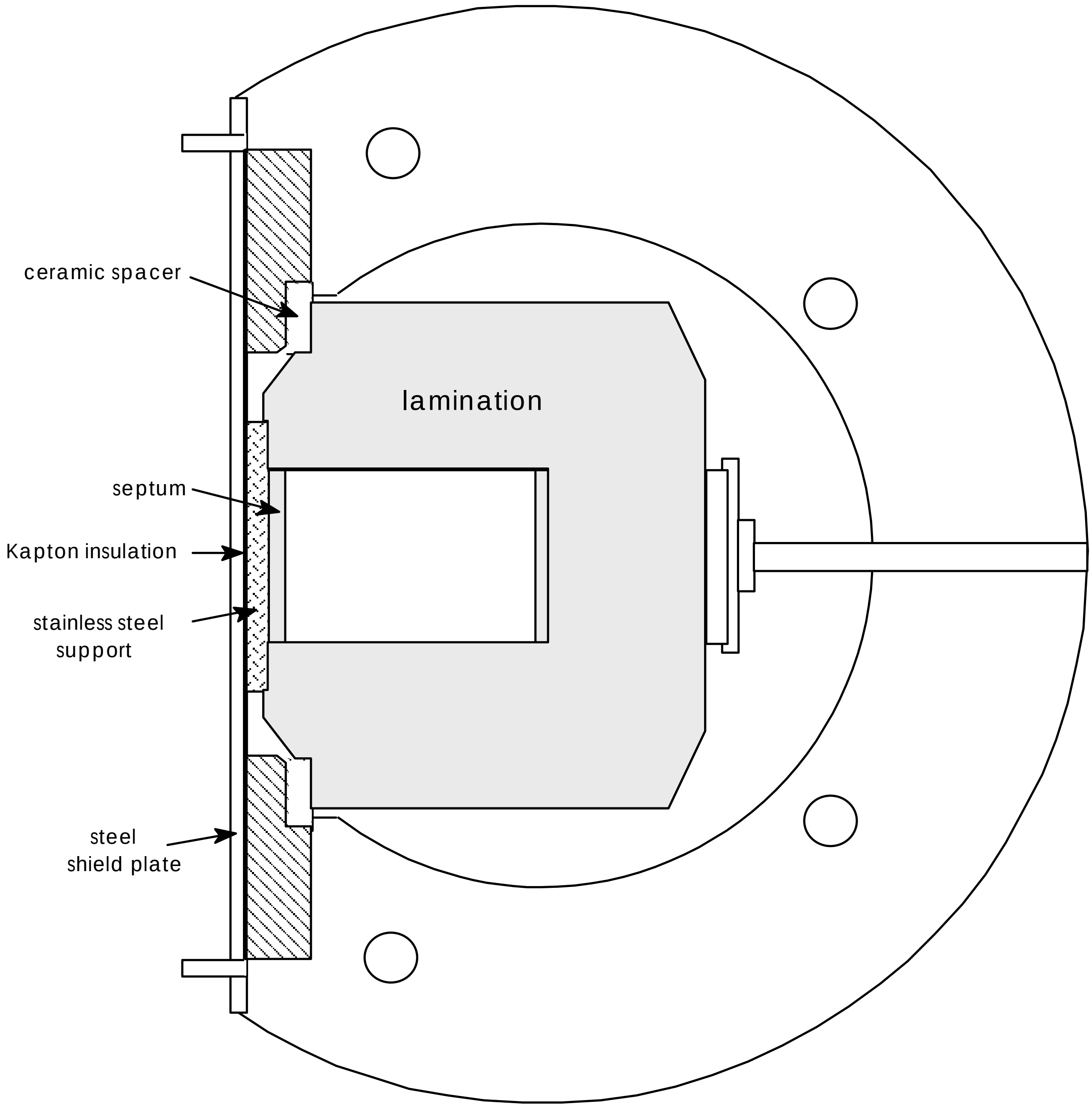

Figure 6.3 Debuncher extraction septum cross section

2. Septa

There are five septa magnets found in the pbar rings, four of them are of a single turn design. Debuncher injection and extraction as well as Accumulator injection (two septa are used here) utilize the single turn pulsed septum. Each septum is 2 meters long and is made by stacking "c" shaped steel laminations in a fixture with a slight (50 m radius) curvature for improved aperture. The vacuum enclosure doubles as a stacking fixture for the magnet. Figure 6.3 provides a cross section of a septum magnet. The septum itself is about 1.3 cm thick (the entire septum magnet assembly has a diameter of about 25 cm) and is made up of four parts. A copper conductor is bonded to a stainless steel plate, both carry the current pulse (the steel plate provides support). A sheet of kapton insulates the conductors from a low carbon steel plate used to magnetically shield the circulating beam adjacent to the septum magnet. The conductor carries up to 20,000 Amps to produce a field of 6,000 Gauss (as compared to 500 Gauss for the kickers).

The Accumulator extraction septum is of a Lambertson style made up of a field free region for circulating beam and a field region for extracted beam. The Lambertson is normally powered at all times to prevent tune and orbit shifts that would accompany changing its state. Stray fields in the "field free" region of the Lambertson are small enough to be compensated for.

D. AP1

AP1 is approximately 570 feet long from the beginning of the extraction channel at F17 in the Tevatron enclosure to its terminus at the production target in the Vault. Vertically the line changes elevation from that of the P2 line in the Tevatron enclosure to seven feet higher at the production target. The AP-1 line’s design was predominately driven by the need to efficiently transport 120 GeV protons from the old Main Ring to the target vault. An additional requirement was that the proton beam be focused to a small spot size on the production target. With this consideration in mind, the optics of the AP1 line can be broken down into three sections.

The first section runs from the extraction channel through PB5 (M:Q105) and was designed to cancel horizontal dispersion from the Main Ring. Though beam no longer comes from the Main Ring, the P2 line was designed so that the lattice functions closely matched those in the old Main Ring. The extraction channel is formed by two 162 inch-long Lambertson magnets followed by two 118.4 inch C-magnets that together bend the extracted beam upwards by 32.6 mrad. To make room for the extraction system, the Main Ring B-2 dipoles at F17-4,5 were replaced by a double strength dipole.

Downstream of the extraction channel, beam continues upward and to the outside (from the perspective of the P2 line). Horizontal trim P0-HT (M:HT100) follows which was originally intended to compensate for the difference in angle at F17 between the injected and extracted beams. A four-dipole string, composed of PB1&2 and PBR1&2 (M:HV100), is next. The second pair of dipoles in this string is rolled 38° to allow both vertical and horizontal bending (the "R" in the magnet name stands for "rolled"). Quadrupole PQ1 (M:Q101) follows and then AP1 passes through a ‘sewer pipe’ of about 76 feet and on to the Pretarget enclosure. The first element in this enclosure is trim PQ1-VT (M:VT101) and is closely followed by PQ2 (M:Q102). A series of four dipoles, the first of which is rolled 45°, PBR3 and PB3-5 (M:HV102), follow.

The second section acts to cancel vertical dispersion. It includes PQ3 (M:Q103), PQ4 (M:Q104), and PQ5A&B (M:Q105). A horizontal trim dipole, PQ5-HT (M:HT105), is next and is followed by two vertical dipoles, PBV1 & 2 (M:V105), which straighten out the upward climb of the beam towards the target.

The final section is composed of eight quadrupoles in four circuits, PQ6A&B (M:Q106), PQ7A&B (M:Q107), PQ8A&B (M:Q108), and PQ9A&B (M:Q109I&V). These elements provide the final focus for the proton beam to minimize the spot size on the target (leading to maximized antiproton yield). A horizontal trim, PQ7-HT (M:HT107), is located just upstream of the final quad doublet and a vertical trim, PQ8-VT (M:VT108), just downstream. These trims are used to finely tune the beam’s position on the target to about ± 7 mm. This third section is coincidentally housed totally within the Prevault enclosure. Table 2 lists all AP1 magnetic elements.

Since AP1 operates at two significantly different energies, 8 and 120 GeV, all magnetic elements except trim dipoles are energized by two different supplies depending on the beam energy. Built in safeguards prevent both supplies from being energized simultaneously. The bipolar 25 Amp trim supplies are sufficient for both modes of operation.

AP1 line power supplies with the exception the supply powering the F17 Lambertsons and C-magnets (F2 for M:F17LAM and M:F17DC) are found in the F23 service building.

ELEMENT	120 GeV POWER SUPPLY	8 GeV POWER SUPPLY	TYPE OF DEVICE	COMMENTS
Lambertson #1	M:F17LAM	M:F17DC	F17 ramped/DC Lambertson	critical device rolled 6°
Lambertson #2	M:F17LAM	M:F17DC	F17 ramped/DC Lambertson	critical device rolled 6°
C-magnet #1	M:F17LAM	M:F17DC	F17 Vertical dipole	critical device
C-magnet #2	M:F17LAM	M:F17DC	F17 Vertical dipole	critical device
P0-HT	M:HT100	M:HT100	20" bump	
PB1	M:HV100	M:HV200	EPB dipole	critical device
PB2	M:HV100	M:HV200	EPB dipole	critical device
PBR1	M:HV100	M:HV200	EPB dipole	critical device, rolled 38°
PBR2	M:HV100	M:HV200	EPB dipole	critical device, rolled 38°
PQ1	M:Q101	M:Q201	3Q120 quad	
PQ1-VT	M:VT101	M:VT101	35" bump	
PQ2	M:Q102 M:Q102R='+'	M:Q202 M:Q102R = '-'	3Q120 quad	M:Q102R is a reversing switch
PBR3	M:HV102	M:HV202	AIRCO dipole	rolled 45°
PB3	M:HV102	M:HV202	AIRCO dipole	
PB4	M:HV102	M:HV202	AIRCO dipole	
PB5	M:HV102	M:HV202	AIRCO dipole	
PQ3	M:Q103	M:Q203	3Q120 quad	
PQ4	M:Q104	M:Q204	3Q120 quad	
PQ5A	M:Q105	M:Q205	3Q120 quad	
PQ5B	M:Q105	M:Q205	3Q120 quad	
PQ5-HT	M:HT105	M:HT105	35" bump	
PBV1	M:V105	M:V205	AIRCO dipole	
PBV2	M:V105	M:V205	AIRCO dipole	
PQ6A	M:Q106	M:Q206	3Q120 quad	
PQ6B	M:Q106	M:Q206	3Q120 quad	
PQ7A	M:Q107	M:Q207	3Q120 quad	
PQ7B	M:Q107	M:Q207	3Q120 quad	
EB6		D:H926	SDD dipole	OFF for stacking, critical device
PQ7-HT	M:HT107	M:HT107	35" bump	
PQ8A	M:Q108	M:Q208	3Q120 quad	
PQ8B	M:Q108	M:Q208	3Q120 quad	
PQ8-VT	M:VT108	M:VT108	40" bump	
PQ9A	M:Q109I, M:Q109V	M:Q209	3Q120 quad	
PQ9B	M:Q109I, M:Q109V	M:Q209	3Q120 quad	

Table 2 AP1 Magnetic Elements

1. 120 GeV

120 GeV protons from the Main Injector are extracted in a single turn initiated by a kicker located at MI-52. A series of Lambertson magnets downstream of the kicker bends beam vertically into the P1 line. Beam is directed down the P1 line, then passes into the P2 line at F0 in the Tevatron enclosure. A Lambertson magnet at F0 directs beam downward into the Tevatron when it is powered, so it's left off when beam is desired in the P2 line. The P2 line, sometimes referred to as the "Main Ring remnant", transports the beam between F0 and F17 where the AP-1 line begins. Although Lambertson magnets are no longer required to bend beam into the AP-1 line, (conventional dipoles would suffice) the original F17 Lambertson magnets remain. With the decommissioning of the Main Ring, the Lambertsons were moved horizontally so that beam always passes through the center of the field region (see Figure 6.4). If beam is destined for the P3 line, the Lambertsons are simply not powered. The two Lambertson magnets and the two 'C' dipoles that follow are powered in series at 120 GeV by a single power supply located at F2 known as M:F17LAM. It is a former Main Ring bend power supply, which has been specially modified for its current use. When stacking, the magnets are ramped to reduce power consumption as well as to reduce the heat load on the magnets. Additionally, the magnets powered by M:HV100 and M:HV102 are also ramped (via 165 cards) to reduce cable heat load and conserve power.

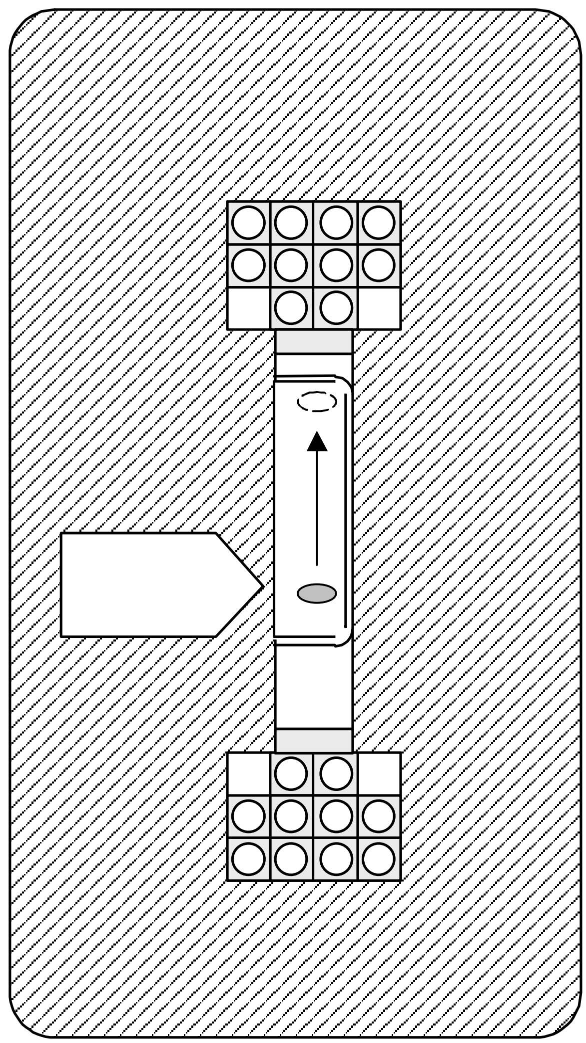

Figure 6.4 F17 Lambertson cross section

2. 8 GeV

AP1 magnets are run at a much lower current for 8 GeV than 120 GeV operation. It would be prohibitively expensive to have power supplies designed to regulate well at both current levels so separate power supplies are used for the two modes. Although M:HV100 and M:HV102 are ramped for 120 GeV operation, M:HV200 and M:HV202 are run DC for 8 GeV beam.

When AP1 is used to transfer pbars into the Main Injector, the first four quadrupoles, PQ7A&B (M:Q207) and PQ6A&B (M:Q206), encountered by the antiproton bunches are used to match the optics of AP1 and AP3. Note that PQ8A&B (M:Q208) and PQ9A&B (M:Q209) are bypassed by the AP3 line, the 8 GeV supplies are only needed on the infrequent occasions when 8 GeV protons are transferred to the Debuncher via AP2.

The AP1 lattice is altered for 8 GeV operation by reversing the polarity of PQ2 (the quadrupole is changed from horizontally defocusing to horizontally focusing). Since the quadrupole power supplies are not bipolar, a separate reversing switch, M:Q102R, is used for the polarity reversal. This switch was added after the first collider run to reduce the size of the extracted beam at PQ3. The original lattice design had caused poor efficiency during antiproton transfers.

E. AP2

Following the lithium lens (D:LNV) in the target vault, a pulsed 3 degree horizontal dipole known as the Pulsed Magnet (D:PMAGV) is used to momentum select negatively charged 8 GeV secondary particles into the AP2 line. The AP2 line then transports the selected particles towards the Debuncher. Most of the secondaries other than antiprotons have a short lifetime and decay during the journey down this beamline. Whatever is left, mostly pions and electrons, does not survive the first few turns in the Debuncher. AP2 was designed to transport an 8 GeV beam with 20π mm-mrad (190π mm-mrad normalized) transverse emittance and a momentum spread of 4%. Table 3 lists the magnetic elements making up the AP2 line.

According to the *Tevatron I Design Report*, the AP2 line can be broken into five parts. The first section, beginning with the Pulsed Magnet, is described as the "clean-up" section. After exiting the target vault, the AP2 line passes through two pairs of quadrupoles and a vertical trim which is located between IQ2 and IQ3 (D:Q702). Another 3° bend to the left by IB1 completes this portion of the line.

A transport section follows, which consists of a FODO lattice of quadrupole cells. These periodic cells have a length of 89 feet. Pairs of horizontal collimators are located immediately downstream of IQ7 and IQ9 (D:Q707). Similarly, pairs of vertical collimators are positioned downstream of IQ8 and IQ10 (D:Q707). Two vertical and a horizontal trim dipole are contained in this section to fine tune beam position: IQ6-VT (D:VT706), IQ11-HT (D:HT711), and IQ11-VT (D:VT711).

Next is a left bend made up of six bending elements, IB2-7 (D:H717), which deflects the beam by 36.53°. Four quadrupoles are interspersed amongst these bending magnets. The elevated horizontal dispersion in the left bend section results in a large horizontal beam size. For this reason, momentum selection can be done in the middle of the section with a set of horizontal collimators.

Another long transport section follows, virtually identical to the first transport, made up of repeating FODO cells. A vertical and horizontal trim dipole are placed in this line downstream of IQ23 (D:Q716) and IQ27 (D:Q719) respectively. IQ24 is no longer connected electrically, it was originally powered by D:Q716 but was disconnected to improve the beamline lattice.

The final portion of the AP2 line is an achromatic vertical translation into the Debuncher called the "injector" section. The section ends at the downstream end of a 2.1 meter current septum magnet. Beam is deflected downward in this portion of the line with a 3.62° bending magnet, IBV1 (D:V730), and is translated 1.3 meters to be at the same elevation as the Debuncher. Three quadrupoles, IQ31-33 (D:Q731), are located in the injector section as well as a pair of horizontal trims, IQ30-HT (D:HT730) and IQ31-HT (D:HT731). A large quadrupole in the Debuncher, D4Q5, has a large aperture to accommodate both the circulating and extracted beam. This large quad is of the same design as those found in the Accumulator high dispersion areas. D4Q5 is powered by both D:IB and D:QT405 for a total of more than 1,500 A. The large quads have fewer windings than the small quadrupoles found at the other DxQ5 locations and require considerably more current to produce the same field strength. Because the AP-2 beampipe is offset from the center of this magnet, a dipole field is imparted on the injected beam

ELEMENT	POWER SUPPLY	TYPE OF DEVICE	COMMENTS
IQ1	D:Q701	SQC	
IQ2	D:Q702	SQC	
IQ2-VT	D:VT702	NDB	
IQ3	D:Q702	SQC	
IQ4	D:Q701	SQC	
IB1	D:H704	modified B1	Critical device
IQ5	D:Q701	SQC	
IQ6	D:Q701	SQC	
IQ6-VT	D:VT706	NDB	
IQ7	D:Q707	SQC	
IQ8	D:Q707	SQC	
IQ9	D:Q707	SQC	
IQ10	D:Q707	SQC	
IQ11	D:Q707	SQC	
IQ11-HT	D:HT711	NDB	
IQ11-VT	D:VT711	NDB	
IQ12	D:Q707	SQC	
IQ13	D:Q707	SQC	
IQ14	D:Q707	SQC	
IQ15	D:Q715	SQA	
IQ16	D:Q716, D:QS716	SQB	
IQ17	D:Q716, D:QS717	SQD	
IB2	D:H717	6-4-120 wide gap	Critical device
IQ18	D:Q718	SQB	
IB3	D:H717	6-4-120 wide gap	Critical device
IB4	D:H717	SDE wide gap	Critical device
IQ19	D:Q719, D:QS719	SQB	
IQ20	D:Q719, D:QS720	SQB	
IB5	D:H717	SDE wide gap	Critical device
IB6	D:H717	6-4-120 wide gap	Critical device
IQ21	D:Q718	SQB	
IB7	D:H717	6-4-120 wide gap	Critical device
IQ22	D:Q716, D:QS722	SQD	
IQ23	D:Q716, D:QS723	SQD	
IQ23-VT	D:VT723	NDB	
IQ24		SQA	not powered
IQ25	D:Q716	SQD	
IQ26	D:Q719, D:QS726	SQA	
IQ27	D:Q719	SQA	
IQ27-VT	D:HT727	NDB	
IQ28	D:Q719, D:QS728	SQA	
IQ29	D:Q729, D:QS729	SQD	
IQ30	D:Q729, D:QS730	SQD	
IBV1	D:V730	modified B1 wide gap	Critical device
IQ30-HT	D:HT730	vernier trim	
IQ31	D:Q731, D:QS731	SQE	
IQ31-HT	D:HT731	vernier trim	
IQ32	D:Q731, D:QS732	SQE	
IQ33	D:Q731, D:QS733	SQE	
D4Q5	D:QT405, D:IB	LQE	
ISEP	D:ISEPV	pulsed septum	
IKIK	D:IKIK	3-module kicker	

Table 3 AP2 Magnetic Elements

providing an upward bend. A pulsed magnetic septum, ISEP (D:ISEPV), and 3-module kicker magnet, IKIK (D:IKIKV), complete the injection line.

Power supplies for AP-2 line magnets in the upstream part of the line are located in AP0, those located in the middle of the line can be found at F27, and downstream supplies reside in AP50.

F. Debuncher to Accumulator (D to A)

Beam is transferred horizontally from the Debuncher into the Accumulator in the 10 straight section. Extraction from the Debuncher is accomplished with a 3-module kicker, EKIK (D:EKIKV), and septum, ESEP (D:ESEPV) combination. The quadrupole in the Debuncher just downstream of the septum, D6Q6, is a large style quadrupole used in much the same way as D2Q5 is at the end of the AP2 line. In this case beam passes horizontally off-center through D6Q6 providing a greater bend towards the Accumulator. The D to A line has a vertical trim between the first two quadrupoles, and a horizontal trim between the second and third quadrupoles. Another vertical trim as well as a major bend, TB1&2 (D:H807A&B), are found between the sixth and seventh quadrupoles. The vertical trims can be used together to control the vertical position and angle at injection into the Accumulator. The two horizontal dipoles can control the horizontal position and angle at injection. Beam passes through a septa pair, ISEP2 (A:ISEP2V) and ISEP1

ELEMENT	POWER SUPPLY	TYPE OF DEVICE	COMMENTS
EKIK	D:EKIK	3-module kicker	
ESEP	D:ESEPV	pulsed septum	
D6Q6	D:QT606, D:IB	LQE	
TQ1	D:Q801, D:QS801	SQE	
TQ1-VT	D:VT801	NDB	
TQ2	D:Q801, D:QS802	SQD	
TQ4-HT	D:HT804	NDB	
TQ3	D:Q801	SQD	
TQ4	D:Q804, D:QS804	SQC	
TQ5	D:Q804	SQD	
TQ6	D:Q804, D:QS806	SQD	
TQ6-VT	D:VT806	NDB	
TB1	D:H807A	modified B1	
TB2	D:H807B	modified B1	
TQ7	D:Q807	SQA	
ISEP2	A:ISEP2V	pulsed septum	
ISEP1	A:ISEP1V	pulsed septum	
IKIK	A:IKIKV	shuttered kicker	

Table 5 D to A line Magnetic Elements

(A:ISEP1V), and then is kicked onto the Accumulator injection orbit with a shuttered kicker, IKIK (A:IKIKV), in the A20 high dispersion straight section. All D to A line power supplies are located in the AP10 service building except A:IKIKV which is located at AP-30.

G. AP3

This transport line can be separated into five sections: extraction, a long transport, a left bend, another long transport and a target bypass. When beam is extracted from the Accumulator, a shuttered kicker in the A20 high dispersion straight section kicks beam on the extraction orbit (radially outside) horizontally so that when the kicked beam reaches straight section 30 it passes through the field region of a Lambertson magnet, ELAM. Both the extraction and injection kickers used in the Accumulator have shutters to prevent the core from being disturbed by fields from the kicker. A metal shutter moves into the aperture between the injection/extraction orbit and the high energy edge of the stack tail shortly before the kicker fires and retracts afterwards. ELAM bends beam upwards and out of the Accumulator and a 'C' magnet just downstream of the Lambertson supplies an additional upward bend. These devices, both powered by the D:ELAM power supply, raise the extracted beam to a level four feet above the Accumulator. Two separate downward bends, EBV1&2, of 50 mrad each level the extracted beam at the same height as the production target. In the extraction channel there are also five quadrupoles, EQ1, 2, 3A&B, and EQ4, and a horizontal trim, EQ1-HT.

After the down/leveling bends, beam passes through the first long transport consisting of ten quadrupoles, EQ5-14. This has a repeating FODO lattice similar to the long transport sections of the AP2 line, although the cell length is longer. A cluster of three trims, EQ6-HTA, EQ6-VT, EQ6-HTB, is located at the upstream (as seen by pbars) end of this section.

A bend to the left, EB1-3, follows. There are two quadrupoles. EQ15, 16, located in the bend section. Beam then is directed through a second long transport, which is similar to the previous one. This long transport runs parallel to the first long transport in the AP2 line. This section includes nine quadrupoles, EQ17-25, and vertical trims, EQ17-VT & EQ25-VT, at each end.

ELEMENT	POWER SUPPLY	TYPE OF DEVICE	COMMENTS
EKIK	A:EKIK	shuttered kicker	
ELAM	D:ELAM	80” Lambertson	
C- magnet	D:ELAM	30” ‘C’ magnet	
EQ1	D:Q901	SQC	
EBV1	D:V901, D:VS901	modified B1	Critical device
EQ1-HT	D:HT901	NDB	
EQ2	D:Q901	SQD	
EQ3A	D:Q903	SQD	
EQ3B	D:Q903	SQD	
EQ4	D:Q901	SQB	
EBV2	D:V901, D:VS904	modified B1	Critical device
EQ5	D:Q901	SQC	
EQ6	D:Q901	SQD	
EQ6-HTA	D:HT906A	40” bump	
EQ6-VT	D:VT906	NDB	
EQ6-HTB	D:HT906B	NDB	
EQ7	D:Q907	SQE	
EQ8	D:Q907	SQA	
EQ9	D:Q909	SQA	
EQ10	D:Q909	SQA	
EQ10-HT	D:HT910	NDB	
EQ11	D:Q909	SQA	
EQ12	D:Q909	SQA	
EQ13	D:Q913	SQA	
EQ14	D:Q914	SQA	
EB1	D:H914	SDE	Critical device
EQ15	D:Q913, D:QS915	SQC	
EB2	D:H914	SDE	Critical device
EQ16	D:Q916	SQC	
EB3	D:H914	SDE	Critical device
EQ17	D:Q917, D:QS917	SQA	
EQ17-VT	D:VT917	NDB	
EQ18	D:Q917	SQA	
EQ19	D:Q919, D:QS919	SQB	
EQ20	D:Q919	SQA	
EQ21	D:Q919	SQA	
EQ22	D:Q919	SQA	
EQ23	D:Q919	SQA	
EQ24	D:Q924	SQA	
EQ25	D:Q924, D:QS925	SQA	
EQ25-VT	D:VT925	NDB	
EB4	D:H914, D:HS925	SDE	Critical device
Target bypass			
EQ26	D:Q926, D:QS926	SQB	
EB5	D:H926	SDD	
EQ27	D:Q926	SQC	
EQ28	D:Q926, D:QS928	SQD	
EB6	D:H926	SDD	

Table 4 AP3 Magnetic Elements

The AP3 line then bypasses the target by means of an achromatic transport using three dipoles and three quadrupoles, EQ26-28. The first of the three dipoles, EB4, is electrically connected with EB1-3 which make up the left bend. Following EB4, AP3 departs the Transport enclosure and bypasses the target station. After the target bypass, AP3 beam enters the Prevault enclosure and encounters two bends, EB5&6, which direct beam into the AP1 line. The final dipole of the target bypass, EB6, is actually in the AP1 line between the tenth and eleventh quad (in the proton direction) of that line. Since it is physically in the AP1 line, its power supply, D:H926, must be off during 120 GeV operation or during studies periods when beam is desired to pass through the target vault.

Three service buildings house AP3 line power supplies: AP30 for the upstream end, F27 for the bulk of the supplies, and AP0 for the downstream portion.

H. Decommissioned beamlines

1. The original AP-1 line

Early designs of the AP-1 line were based on a proton energy of 80 GeV from the Main Ring. The energy was later raised to 120 GeV in order to increase the target yield. Increasing the energy of the proton beam incident on the target increases the yield of 8 GeV antiprotons but also requires a longer Main Ring cycle time. Calculations suggested that a beam energy of 120 GeV was the practical upper limit for extraction energy from a medium straight section. Improvements in the rate of rise of the Main Ring ramp allowed the increase to 120 GeV. However, it also complicated the process of extracting the Main Ring protons and delivering them to the target.

An 80 GeV line existed at one time in the Tevatron enclosure, perched just above the Main Ring and extending from F-17 to F-25. When the increase in proton energy was first proposed, the original plan was to upgrade the 80 GeV line for 120 GeV operation. There were problems with this approach, as the magnets would have been run at a substantially higher current, resulting in a large increase in power consumption. The existing beamline magnets were difficult to maintain and also made work on the Main Ring and Tevatron magnets more complicated. When the Tevatron was installed, the 80 GeV line had to be dismantled to allow enough room to work.

The original pbar target hall, which is in a field outside the Tevatron enclosure near F-26, limited the ability to vary the position on the target. The 80 GeV line had originally been put into the Main Ring tunnel because of the operating schedule. In 1977-78 there was not enough time available to modify the tunnel at F-18 in order to build the more elaborate beamline. Eventually, the problems associated with the higher energy proton beam helped make the decision to build a more efficient and flexible beamline. The new design resulted in a four-fold reduction in power consumption (not only lower energy costs, but smaller and less expensive power supplies) over what an upgraded 80 GeV line would have used.

In the original 120 GeV beam line scheme, a tunnel was to run from the Main Ring to the target vault. There was also to be a separate enclosure to run adjacent to the vault where AP-3 is situated. However, the final beamline includes a "sewer pipe" through which the beampipe passes in AP-1 from the Main Ring to the Pre-Target enclosure. There is no separate enclosure where AP-3 bypasses the target vault, it simply passes through part of the vault.

2. AP-4

The AP4 line was used to transfer 8 GeV protons from the Booster to the Debuncher. This permitted beam studies during periods of extended Main Ring down time when the Booster was operational. Since the protons circulated in the same direction as pbars would have, the power supply/magnet polarities were reversed.

Booster beam was extracted upwards at Long 3 and bent back downwards by a vertical dipole. A vertical dogleg followed the dump and lifted beam to the level of the rings enclosure. Beam was transferred through a "sewer pipe" from the Booster to the rings enclosure. The extraction point from Booster for the former AP-4 line is now used for the MI-8 line. In the Pbar rings enclosure, evidence of the AP-4 line can be found at the upstream end of the 20 sector on the outside of the enclosure. The Debuncher location formerly used by the injection kicker is now occupied by a cooling kicker tank. Even before AP-4 was decommissioned, the kicker was replaced with the cooling tank during running periods. A "large" quad is still in place at D2Q5 where the descending beamline passed through the upper aperture. Like large quads associated with the AP-2 and D/A lines, this quad is powered by a combination of D:IB and a separate supply D:QT205.

VII. Diagnostics

Diagnostic devices are employed in the antiproton source to provide a means of sensing the beam in each of the machines and transport lines. With the low intensity pbar beams, some special devices and modifications were developed to detect the weak signals in a non-destructive manner. Most of the diagnostic devices found in the antiproton source can also be found in other accelerators.

A. DCBCT's

A DCBCT or Direct Current Beam Current Transformer is a device used to measure the quantity of circulating beam with high precision. D:IBEAM and A:IBEAM, the beam current or intensity readbacks for the Debuncher and Accumulator respectively, are sourced from such a device installed in each ring. Accuracy is one part in 10^5 over the range of 3 mA to 85 mA of beam current. As an aside, the revolution period of both the Debuncher and Accumulator for an 8 GeV particle is ~1.6 µs. Based on this coincidence with the units of charge, beam current can easily be converted to intensity:

$$1\ mA = 1 \times 10^{10}\ particles.$$

because

$$\frac{1.6 \times 10^{-19}\ \text{Coulomb/particle}}{1.6 \times 10^{-6}\ \text{second}} = 1 \times 10^{-13}\ \text{Amperes/particle}$$

If there are 10^{10} circulating particles, then the current is:
1×10^{-3} Amp or 1 mA.

The pickups are supermalloy tape-wound toroidal cores with laminations, which act to reduce eddy currents. Beam goes through the hole of the donut and acts as a single turn on the toroid transformer. The beam sensing electronics are attached to wire windings on the toroids. Passing beam induces currents in the toroids and the electronics sense those currents and produces an equal and opposite current that keeps the net toroid current at zero. Referring to figure 7.1, T1 senses the AC portion of the beam while T2, T3, the modulator, and demodulator sense the DC portion. The DC and AC signals are summed in OP1, which drives each toroid just hard enough to cancel the beam-induced currents. T4 and OP2 sense modulator ripple and anything else the OP1 feedback loop may have missed and compensates for it. OP3 measures the drive produced by OP1 and OP2, which is proportional to the beam intensity. The beam signal is actually measured across the resistor R, which resides in the temperature-controlled current to voltage converter upstairs in AP10. The accuracy of the measurement is dependent on the resistance staying constant. An OMEGA temperature controller maintains the resistor's temperature at 100° Fahrenheit. The controller contains an EPROM to retain the last set values in the event of a power failure.

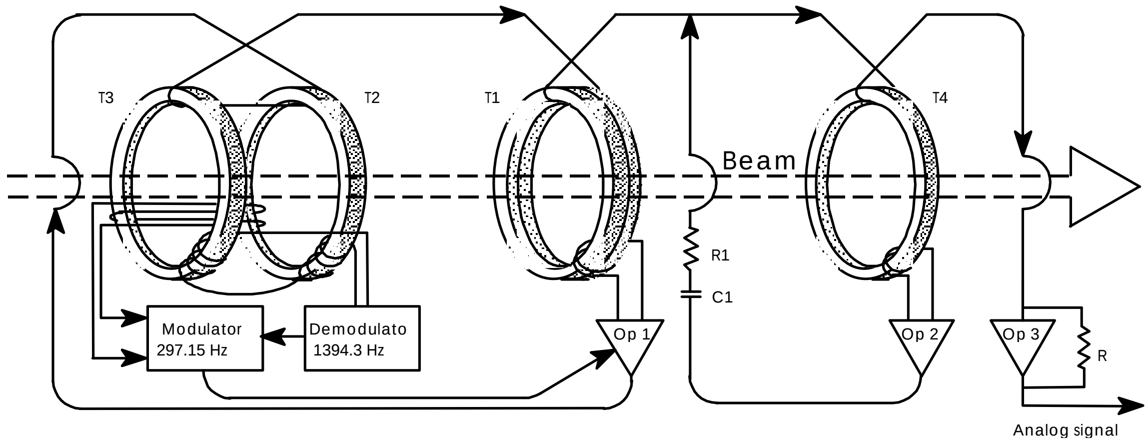

Figure 7.1 IBEAM Direct Current Beam Current Transformer

The DCBCT toroids are contained in 40 inch long by 10 inch diameter structures that reside in straight section 10 of both machines. The signal goes upstairs to AP10 and eventually to Keithley digital voltmeters located in racks in the AP10 control room. A test current can be used to provide 1.2 mA that appears as 1.2 X 10^{10} particles on the IBEAM readback. The switch for the test current is located on the current to voltage converter in the upstairs electronics rack.

B. Beam Position Monitors

The Pbar Beam Position Monitor (BPM) system provides single turn and multi-turn or closed orbit position information with sub-millimeter resolution. Position information is used to correct the orbit and to measure lattice parameters. The Debuncher has 120 sets of pickups and the

Accumulator has 90. They are split-plate, bi-directional electrostatic pickups that are sensitive to a Radio Frequency (RF) structure on the beam, therefore the beam must be bunched for the BPM's to work. Pickups are generally found at quadrupole locations in the lattice. Circular and rectangular pickups are used depending on location; the beam pipe size is small in low dispersion sections and is very large horizontally in areas of high dispersion. Rectangular pickups are used only in the high dispersion sections of the Accumulator. Accumulator high dispersion BPM's are 10 x 30 cm rectangles, Accumulator low dispersion BPM's are cylindrical and have a 13 cm diameter, Debuncher BPM's are cylindrical with an 18 cm diameter. BPM's can also be found in the AP1, 2 and 3 beamlines. Beamline BPM's are located at quadrupole locations and are of the semi-circular design.

1. Debuncher

For the Debuncher system, signals from the pickups are amplified with preamps, which are mounted directly on the beam pipe. There is also a second pair of amplifiers with 46 db of gain that can be switched in. Power supplies for the amplifiers are located upstairs in the service buildings in the BPM racks. Preamp outputs are fed via 1/8-inch hard line to Trontek gain switchable amplifiers that are mounted on the tunnel wall. Trontek amplifiers are also used on Debuncher and some AP-2 BPM's. The Trontek's

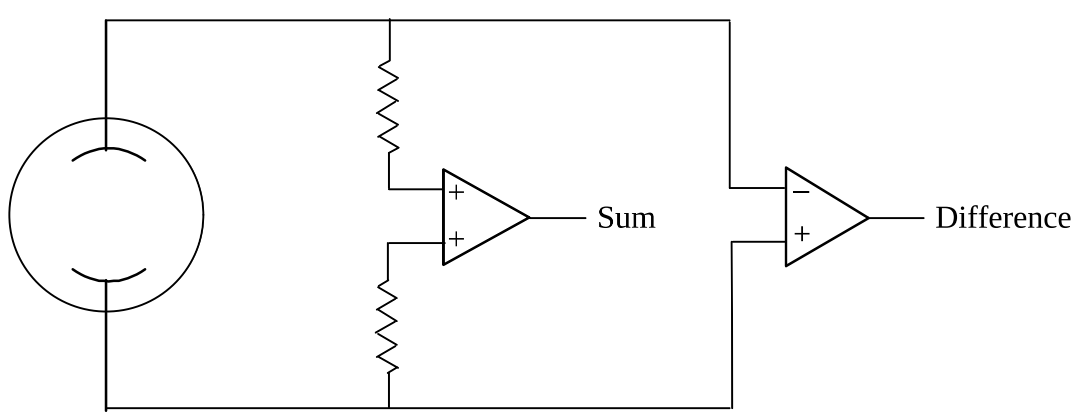

Figure 7.2 Debuncher pickups

have a 20 db and a 40 db amplifier that are selectively switched in line to provide 0, 20, 40, or 60 db gain.

After amplification in the tunnel, the sum and difference signals (see figure 7.2) travel on 3/8-inch heliax to the inputs of the multiplexers upstairs in the service buildings. These multiplexers, which are remnants of the old Main Ring BPM system, have ten inputs. There are two vertical and two horizontal muxes at each service building for the Debuncher. The multiplexer selects one pickup signal per sample period and sends it to the RF modules. A closed orbit measurement is typically the average of 20 individual measurements.

The next set of electronics is one of two types of RF module. The 53 MHz (fast) Tevatron-type module is used to provide turn-by-turn information. The slow RF modules are used for closed orbit information. The Debuncher BPM system has a single Voltage Controlled (X)crystal Oscillator (VCXO) at AP10 which runs at 10 kHz above the harmonic frequency (2.36 MHz) seen by the RF modules. The beam signal and VCXO are mixed to produce a 10 kHz signal, which the op amps in subsequent electronics are able to handle. The VCXO output is split three ways to go to AP10, AP30, and AP50. Once in the building the signal splits again to RF modules at opposite ends of the

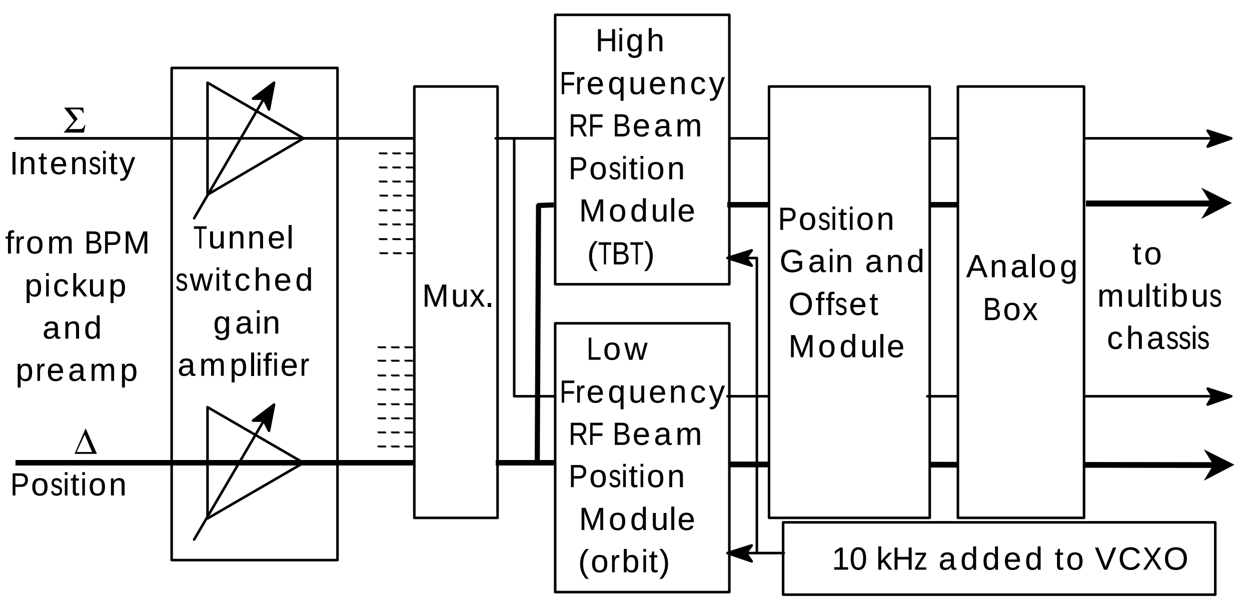

Figure 7.3 Debuncher BPM block diagram

building. The VCXO is tuned over a small range to center the BPM signal in the passband of the filters in the next electronics module. Figure 7.3 provides a generalized BPM block diagram for the Debuncher system.

2. Accumulator

An upgrade to the Accumulator BPM system was finally completed late in 1998. Most changes involved the signal processing and communication hardware, including the use of a VXI platform instead of CAMAC. Both the analog and digitizer VXI cards were designed and built at Fermilab. The beam detectors and preamplifiers remain unchanged from the original system.

Signals from the BPM pickups are amplified by a preamplifier mounted to the beampipe. There are A and B signals corresponding to the two BPM pickup plates. The matched signal paths have independent gain control, in both cases the output of the preamp provides the input for the analog card. This scheme is different from the old Accumulator system and present Debuncher system. Previously sum and difference signals were created by electronics in the tunnel, now the signals are processed in the service buildings. Because the signal strengths from the two pickups are so similar, the cables connecting to the analog card must be precisely matched. Any modification to one of the signals as it travels to the analog card will result in errors in the calculated position.

The analog card has eight inputs made up of four channel-pairs. Each input is gain adjustable with two modes for Turn-By-Turn (TBT) or closed orbit operation. Output from the analog card becomes the input for the digitizer card. The digitizer card also has eight inputs made up of four channel-pairs. Each input provides a 12-bit digitizer and a 128k buffer. The digitizer card has an on-board Digital Signal Processor (DSP) which processes the digitized data. When in TBT mode a position for each turn is calculated, in closed orbit mode an average position is calculated.

The original Accumulator BPM system made use of a reference oscillator signal from an output of the ARF3 low level. With the new system, the expected revolution frequency of the beam is an ACNET device that is set by the user.

In addition to their primary role of detecting beam position, the Accumulator BPM plates also are used as a mechanism to remove trapped

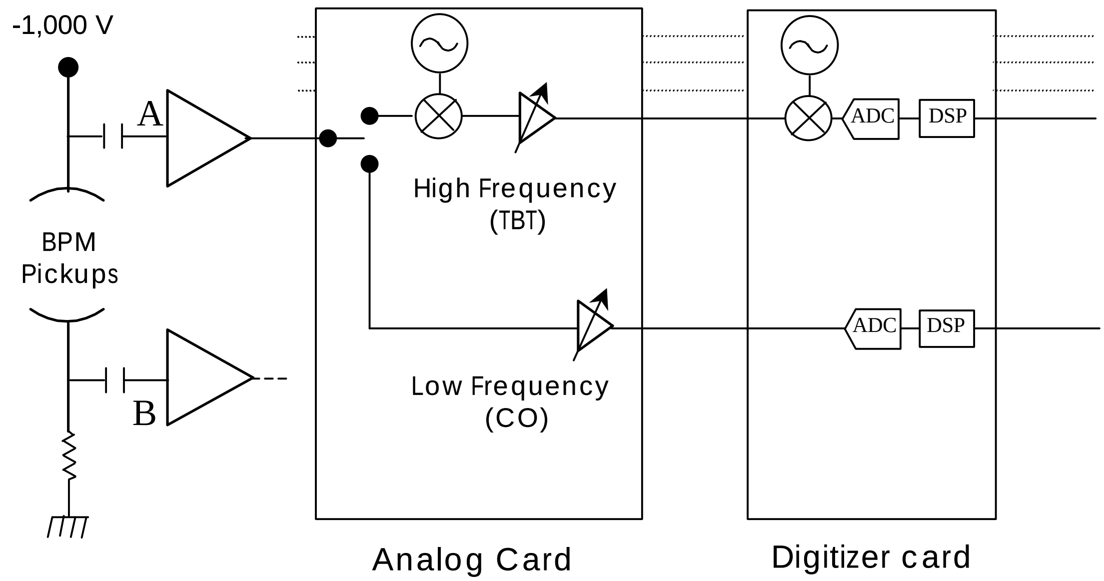

Figure 7.4 Accumulator BPM Box Diagram

positive ions. A –1,000 Volt DC “clearing voltage” is applied to the pickup plates to attract ions. The RF BPM signals are passed to the electronics through blocking capacitors (see figure 7.4).

3. Transport Lines

In the transport lines, amplifiers are used on some of the AP-2 line BPM's to boost the weak signals produced due to the low intensity. When stacking, the number of antiprotons and other negative secondaries (mostly pions) is relatively small, on the order of 6 x 10^9. The beam intensity in the D to A line is even smaller, 10^8 or less, so D to A line BPM's are not reliable when stacking. In the other transport lines, BPM's can be very useful. The primary advantage of BPM's is that they are passive, they do not make direct contact with the beam.

C. Loss Monitors

There are two types of Beam Loss Monitors (BLMs) in the antiproton source, ion chamber and plastic scintillator with a photomultiplier tube (PMT). The ion chamber BLMs can be found in beamlines and are used to monitor losses during stacking and pbar transfers. The plastic scintillator BLMs are distributed throughout the Accumulator and Debuncher rings and can be used for studies or for locating loss points.

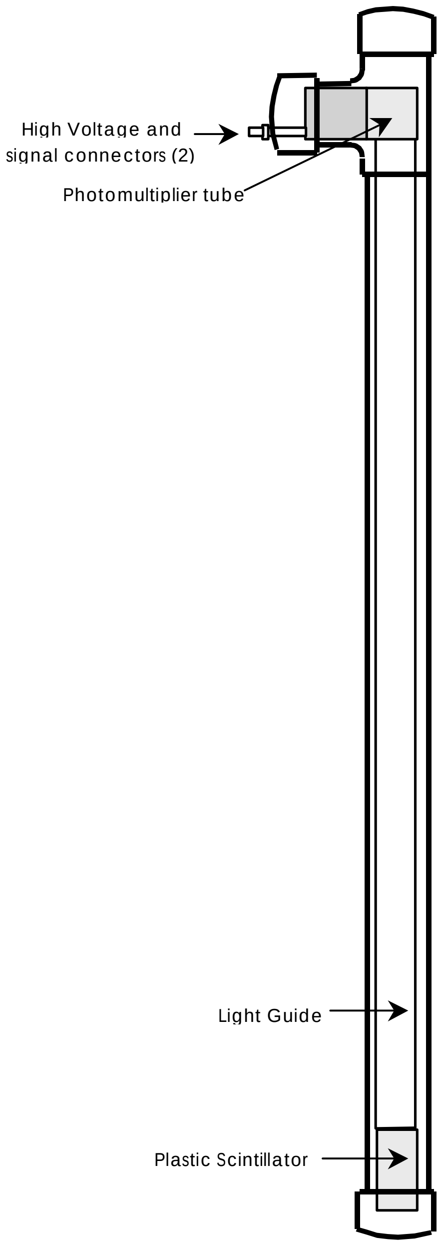

Figure 7.5 Accumulator and Debuncher BLM

The ion chamber monitors are of the same type as those used in the Tevatron. The BLM detector is a sealed glass ion chamber with a volume of 110 cubic centimeters that is filled to 1 atmosphere with Argon. A high voltage power supply is daisy chained to a string of BLMs and provides about a 2,000 Volt bias to the chamber. The output goes upstairs on an RG58 signal cable to a beam loss integrator and then to a Multiplexed Analog to Digital Converter (MADC). The MADC is read by the controls system in the usual way.

A "paint can" style BLM was formerly used in the antiproton source for both the beamlines and rings. They were made up of a photomultiplier tube immersed in scintillating oil. Because the scintillating oil is categorized as hazardous waste, an effort was made to replace the paint cans. The plastic scintillator design BLM retains the sensitivity to small numbers of particles, which the ion chamber loss monitors don't have. The loss monitors are made up of a 4"x2"x$^1/_2$" piece of plastic scintillator glued to a 36" long Lucite light guide (see figure 7.5). At the end of the light guide a small Lucite coupling attaches it to an RCA 4552 PMT. The PMT's were recycled from the old paint cans and are relatively rugged. The intent of the light guide is to keep the scintillator near the magnets but to extend the phototubes up and away from the region of beam loss. This assembly is mounted in a housing made up of PVC pipe and has feed-throughs for the high voltage and signal cables.

High voltage supplies for the BLMs are located in the AP10, 30 and 50 service buildings. Each supply feeds up to 20 BLMs through a Berkeley voltage divider which allows the gains of all the PMT's to be matched by setting the high voltage to each one individually. In actual practice all of the high voltages are run near maximum value.

The BLM output goes to a quad or octal discriminator, which handles four or eight BLMs. It levels the signal spike from the PMT caused by the lost particle and sends a NIM level pulse to a Jorway quad scalar which handles four BLM’s. The scalar is really a pulse counter that counts pulses during the gated period defined by the gate module. A CAMAC 377 card provides start and stop times to the gate module for the gate pulse. Output from the Jorway 84-1 card is sent to the controls system. Plastic scintillator loss monitor electronics count pulses while Tevatron style argon gas loss monitor electronics accumulates charge on an integrator capacitor.

D. Secondary Emission Monitor (SEM) Grids

SEM grids are used to measure the beam profile in the horizontal and vertical planes. SEMs consist of 30 vertical and 30 horizontal titanium strips placed in the path of the beam. Beam particles have elastic collisions with electrons in the strips and dislodges them (see figure 7.6). This causes a current to flow in the strips and sensitive preamplifiers connected to each strip detect this current. For every forty protons or antiprotons passing through the SEM, one electron is dislodged yielding a detector efficiency of 2.5%. A clearing voltage of +100 VDC can be applied to foils placed before and after the strips to improve the work function of the titanium and double the efficiency to 5%. Since some of the beam collides with the titanium strips, SEM grids are not passive devices. Most SEM grids are located in the

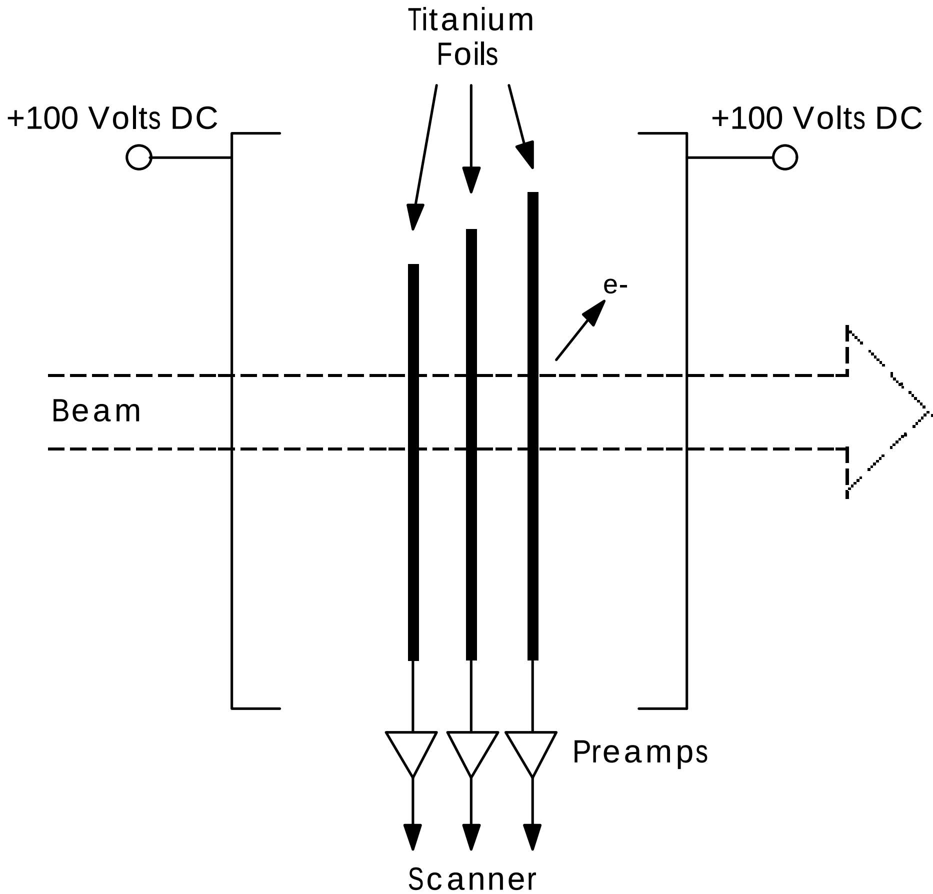

Figure 7.6 SEM grid

transport lines although a few are located near injection and extraction points in the rings to be used during initial tune-up. If one of the ring SEM grids is left in, beam will be rapidly lost.

Motors move the grids for one plane or the other into the beam and are controlled by a CAMAC 181 card. The SEM motor controllers have a safety system input. It retracts the SEM grids from the beam pipe when the beam permit is down. This feature is intended to keep the grids out of the beam pipe should vacuum be broken. Technicians can override this function locally if necessary.

The SEM grids operate at beam pipe vacuum pressure and thus have no gas gain like the Segmented Wire Ionization Chambers (SWICs) found in Switchyard. Preamp boxes are used to amplify the signals generated by the SEM. Preamp boxes contain a pair of mother boards with 30 preamp boards plugged into each (one horizontal and one vertical set). Some versions of the preamp box have charge splitters that when selected attenuates the signal to the preamp 15 times when the charge split input is +5V. D to A line SEMs use preamps that are 260 times more sensitive than those for the other SEMs due to the low beam intensities found during stacking.

Switchyard style SWIC scanners are used for scanning the SEM wires. A

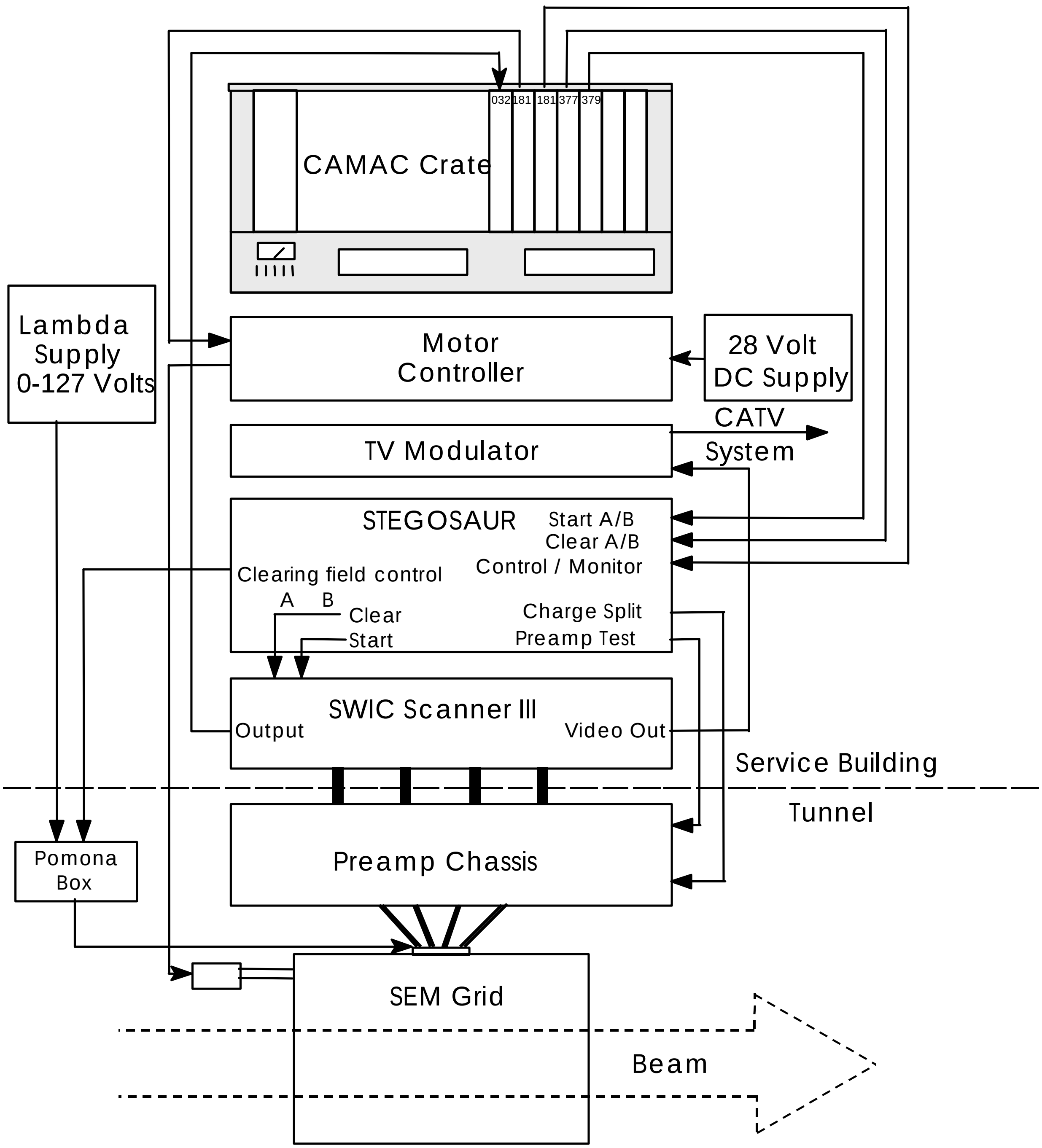

Figure 7.7 SEM block diagram

scanner is made up of: a Z80 based microprocessor, memory and support chips, FET switches and three amplifiers. Scanners receive "clear" and "start" timing and interface with a CAMAC 032 module for communication with the control system (see figure 7.7 for a block diagram of the SEM electronics). The SWIC scanner also has a video output, which goes to modulators upstairs for distribution on the cable TV system. SWIC scanners read the charge accumulated on the sixty integrators tied to thirty horizontal and thirty vertical SEM strips.

SEMs are triggered by STEGOSAURs otherwise known as SEM Test Event Generators (the OSAUR was added to STEG to make it pleasing to the ear). STEGs provide fanout of CLEAR and START timing and test pulsing for up to six SEM grid scanners. Since six SEM grids can be scattered over a long beam line or over adjacent beam lines like AP2 and AP3, STEGs provide an A and B set of clear and start times. The clear time is normally initiated by a CAMAC 377 timer card triggered by a TCLK event. It occurs at least 50 milliseconds before the start trigger. The start time is generally initiated by a CAMAC 379 timer card triggered by a Main Injector Beam Sync (MIBS) event since close synchronization with the beam is necessary (the exception is Debuncher to Accumulator transfer which is not synchronized to the Main Injector).

Other functions of a STEGOSAUR are to synchronize preamp test pulse timing, clearing field control, and charge splitter control for the SEM grid scanners. Control is provided by a CAMAC 181 card. The preamp test is used to test the connection between the preamp chassis and the scanner by connecting a fixed signal to all of the strips on the SEM grid. The clearing field control checks that the foil strips are correctly clearing charge shortly before the start time goes out, this will not alter the display of a SEM that is working correctly.

E. Scrapers

Scrapers are devices that can be used to block off part of the accelerator aperture. A physical analogy would be a gate valve in a water line. The scraper could be used to trim the halo off of the beam, to measure the acceptance of the machine, or to define the emittance of the beam. There are presently ten scrapers in the pbar source:

D:RJ306: Debuncher horizontal (Right Jaw) scraper. It enters the beam from the inside of the ring. It is adjacent to D3Q7.

D:TJ308: Debuncher vertical (Top Jaw) scraper. It enters the top of the ring, traveling 1 7/8 inches. It is located adjacent to D3Q8.

D:RJ410/D:LJ410: Debuncher momentum scrapers. These are horizontal scrapers that are placed in a high dispersion region to allow one to measure the momentum spread, DP/P, of the beam. They are located between D4Q10 and D4Q11.

A:RJ500/A:LJ500: Accumulator horizontal scrapers. They enter the beam from the inside and outside of the ring. They are located near A5Q1.

A:TJ307/A:BJ307: Accumulator vertical scrapers. They enter the beam from the top and bottom of the ring. They are located adjacent to A3Q7.

A:RJ314/A:LJ314: Accumulator momentum scrapers. They are horizontal scrapers in a high dispersion region. They are located in the center of the A40 straight section.

Scrapers are moved with stepping motors and the scraper position is determined with a Linear Variable Differential Transformer (LVDT). Stepping motors allow small and fairly precise position changes. An LVDT puts out a voltage proportional to the position of a slug within a ferrite cylinder with a series of windings. The controlling electronics for the stepping motors are located in the AP-30 and AP-50 service buildings, two CAMAC 057 cards are used to control them. Each scraper has a motor controller card (just like Switchyard septa have). A brown lambda supply provides +24 volts for the motor and +/-15 volts for the LVDT on each scraper.

Incidentally, there are a number of other moveable devices scattered around both pbar rings that operate on the same principle. These devices are normally moved to either electrically center them (as in stochastic cooling tanks), to improve the aperture (Diagnostic devices) or to provide an orbit bump (dipoles that can be rolled and quadrupole magnets that can be moved vertically). For example, the Debuncher Schottky pickups are moveable. They have an "MS" prefix for "Moveable Stand" and have the cryptic ACNET names:

D:MSSCV1 Vertical Schottky Stand
D:MSSCH1 Horizontal Schottky Stand

F. Collimators

Much like their scraper counterparts in the rings, collimators are used to skim the halo off the beam, define the emittance of the beam, and measure the acceptance of a beam line. Although the devices themselves are virtually the same, a scraper is found in an accelerator and a collimator is found in a beam line. All of the collimators are located in the AP2 line and use the same type of electronics as the scrapers. The CAMAC 057 control card and the motor controllers are located in the AP0 service building.

There are two sets of horizontal, two sets of vertical and one set of momentum collimators in the AP2 line. All are of similar construction. The momentum collimator is placed in the left bend section of the beamline where the horizontal dispersion is high. The magnets and collimator act like a mass spectrometer. The ACNET collimator names are:

D:RJ707/D:LJ707: Right and Left Jaw (as you face the Debuncher) of a horizontal collimator placed just downstream of IQ7.

D:TJ708/D:BJ708: Top and Bottom Jaw of a vertical collimator placed just downstream of IQ8

D:RJ709/D:LJ709: Another horizontal collimator located just downstream of IQ9.

D:TJ710/D:BJ710: Another vertical collimator located just downstream of IQ10.

D:RJ719/D:LJ719: The jaws for the momentum collimator located in the middle of the dipoles that make the left bend, just downstream of IQ19.

G. Toroids

Pearson single turn large aperture toroids are located in the transport lines to monitor beam intensity. They are beam transformers that produce a signal that is proportional to the intensity (1V for every 1A of current). The toroids make use of integrators that sample over a gated period that is defined by an MRBS timer. M:TOR109, for example, uses the timing event M:TR109S to start the sample period. The output of the integrator is sampled and held for an A/D conversion.

M:F16TOR is located in the P2 line and is used to monitor beam intensity entering the line during a pbar transfer. It was originally used for measuring beam entering the Main Ring and the gating was set up to sample the pbars on the first turn. The gate is now wide enough to sample a full Booster batch of 84 bunches. However, the readback saturates at an intensity of 2E11 so it is not useful during stacking.

M:TOR105 is located in the Pre-Vault enclosure just upstream of P6QA and is used to monitor proton or antiproton intensities in the AP-1 line. M:TOR109 is also in the Pre-Vault enclosure just upstream of the target vault, and gives a good indication of the number of protons entering the vault and striking the target.

D:TOR704 is located just downstream of the vault and measures the flux of negative secondaries, most of which are negative secondaries other than pbars, entering AP-2. There is another toroid at the end of the AP-2 line, D:TOR733. Like TOR704, TOR733 will measure all of the negative secondaries passing through, whether pbars or not. Unfortunately the beam intensity in the AP-2 line during stacking is too low for the toroids to be an effective diagnostic.

There is one toroid located in the AP-3 line, D:TOR910, which is located between EQ10 and EQ11. This toroid is used both to measure reverse injected protons directed down the AP-3 line and also for measuring pbars extracted during a shot.

Originally there were toroids located near the IQ17 and IQ28 quadrupoles in the AP-2 line and the TQ6 quadrupole of the D/A line. They were removed due to lack of use and to open up the aperture by removing the restricted beampipe that they surround. There is also a toroid 100 in the AP-1 line, but it is no longer connected.

H. Ion Chamber

There is only one ion chamber in use in the antiproton source and that is D:IC728. This ion chamber is located downstream of IQ28 and is used to measure the flux of negative secondaries near the end of the AP-2 line during stacking cycles. Most of the negative secondaries are not pbars but the total flux should still give an approximate indication of the pbar intensity.

The ion chamber has a high voltage electrode at -300V and a signal electrode contained in a chamber filled with helium gas. Secondary particles traveling down the AP-2 line pass through the chamber and ionize the helium resulting in a current path to the signal electrode. The result is a signal proportional to the beam intensity.

A small amount of helium passes out of the ion chamber through a bubbler, however the loss rate is very small. Helium bottles for D:IC728 are found in the AP50 service building. The signal from the ion chamber is digitized and sent to a scalar card. There is a start and clear time used to gate the scalar card. The start time (D:IC728S) is provided by a CAMAC 379 card referenced to an MIBS timer and the clear time (D:IC728C) is provided by a CAMAC 377 card using a TCLK reference.

An ion chamber is able to measure smaller beam currents than a toroid so it is an appropriate choice for the AP-2 line. Ion chambers also formerly existed at the upstream end of the AP-2 line (D:IC704) and in the D/A line (D:IC806) but both were replaced with toroids. The ion chambers have a tendency to leak gas into the beampipe so all but D:IC728 were removed. Unfortunately the toroids that replaced them have difficulty resolving the small beam intensity.

I. Schottky Signals

A charged particle passing through a resonant stripline detector or a resonant cavity creates a small signal pulse known as a Dirac pulse. A particle beam is made up of many charged particles and creates a signal called Schottky noise. Schottky noise is a collection of signal pulses in the time domain, which corresponds to a spectrum of lines in the frequency domain. The lines occur at harmonics of the revolution frequency since the particles circle the accelerator and pass repeatedly through the pickup. The combined response from all the particles in the ring is smeared over a finite frequency range (Schottky bandwidth) at each harmonic. This frequency range is related to the momentum spread of the beam by

$$\frac{df}{f} = \frac{dp}{p}\eta$$

where η (eta, the slip factor) is fixed by the machine lattice (-.012 for the Accumulator, -.006 for the Debuncher).

The revolution period of beam in the Debuncher is 1.695 µs, therefore the revolution frequency is 590,035 Hz or .590035 MHz. In the Accumulator the revolution period of the beam varies between 1.5904 µs at the injection orbit to 1.5901 µs at the core. This corresponds to revolution frequencies of .628766 MHz and .628881 MHz respectively. The Debuncher revolution frequency is lower than that of the Accumulator because the Accumulator has a smaller circumference.

Signals from the Schottky detectors can be displayed on signal analyzers. A coaxial relay mux (the mux box) at AP10 has eight inputs and eight outputs (not all are used) and is used to remotely connect a signal of interest to one of the analyzers. There are six Schottky detectors, which can connect to one of the four spectrum analyzers (analyzer #3 is always connected to the Accumulator longitudinal schottky) via the mux box.

Schottky pickups (or detectors) are devices that are used to detect Schottky noise. There are six Schottky pickups used in the Antiproton Source. The Accumulator and Debuncher each have vertical, horizontal, and

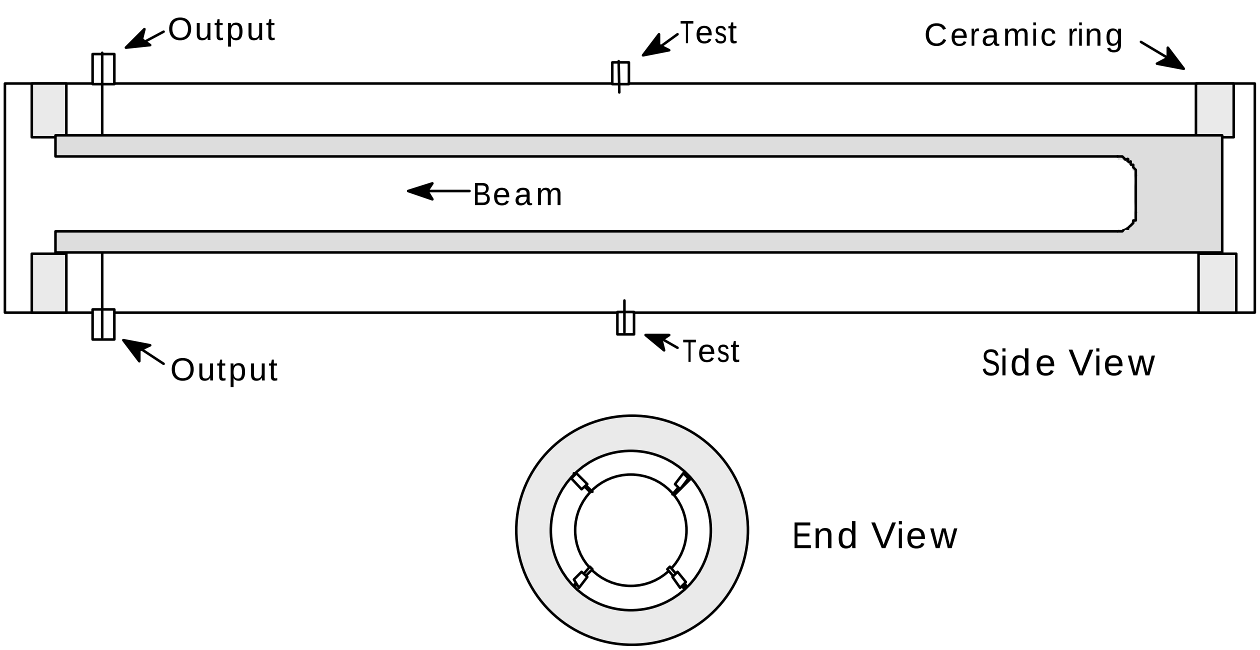

Figure 7.8 Vertical Schottky pickup

longitudinal pickups in the 10 straight section. The vertical and horizontal transverse pickups are approximately 24 inches long and 2 inches in diameter. These pickups detect transverse beam oscillations. The vertical pickup has the striplines above and below the beam with outputs on the top and bottom, the horizontal pickup is rotated 90°. The transverse pickups are a stainless steel tube with a slot cut along much of the long dimension (see Figure 7.8). The pickup is held by ceramic rings, which also electrically insulate it from the outer housing.

Signals from each plate are fed through to a 3/8-inch heliax cable, which is run to the AP-10 service building. Signals are not run directly to the MCR because of the signal loss that would result from the long cable run. The detectors resonate at a frequency determined by the length of the strip inside the cylinder plus the coaxial cable between the output connector and a capacitor. Connectors in the middle are used to inject a signal for tuning the device to the frequency of interest. Horizontal and vertical pickups are mounted on motorized stands so that the device can be centered with respect to the beam.

The longitudinal pickups are larger, 37 inches in length and 3.4 inches in diameter. These pickups are tuned quarter-wave cavities that are made by separating a stainless steel tube into two sections with a ceramic across the gap. Charged particles crossing the gap produce Schottky signals. The longitudinal detectors are tuned with plungers or sliding sleeves on the center element. Again, the unused fittings seen on the cavities are used to inject signal for tuning purposes.

The Schottky detectors used in the Antiproton Source are designed to be most sensitive to the 126th harmonic of the beam's revolution frequency. Although signals at or around the 126th harmonic are usually the strongest in these detectors, signals for other harmonics can also be detected. The Schottky signals weaken as you get further away from the 126th harmonic.

There are several reasons for choosing the 126th harmonic for the design of the Schottky detectors. The spectral power contribution from the 53.1 MHz bunch structure (from ARF-1 in the Accumulator) is minimized by using a frequency located between 53.1 MHz (h=84) and its second harmonic at 106.2 MHz (h=168). The resulting signal from the revolution harmonic for the Accumulator core would be 126*.628881 MHz = 79.239 MHz. The physical size of the detector must also be taken into account. The aperture must be large enough to not restrict beam transmission. Limited space available in the rings limits the pickup length to only 1 or 2m. Schottky detectors designed for the 126th harmonic fit both of these size constraints. For example, recall that the longitudinal Schottky pickups are 1/4 wavelength long. The physical length of the cavity as built is .94 meters ($\frac{1}{4*126}$ of the Accumulator circumference) which would result in a resonant frequency of:

$$f = \frac{\text{velocity}}{\text{length}} \sim \frac{3E8 \text{ m/s}}{4 * .94 \text{ m}} \sim 79.75 \text{ MHz.}$$

That works well for the Accumulator, but the Debuncher h=126 falls at 74.34 MHz (126 * .590035 MHz) so a tuning screw is added to its longitudinal pickup to capacitively lower the resonant frequency of the cavity.

Schottky pickups have many diagnostic uses. They are used to measure the betatron tune, synchrotron frequency, transverse emittance and momentum spread. They can also be used to accurately measure small beam currents. The DCBCTs have an accuracy of about ±2nA. The Schottky pickups can be calibrated against the DCBCTs at beam currents up to around 100 mA and the spectrum analyzers will hold accuracy for smaller currents than the DCBCT. The spectral power of the signal is proportional to the number of particles in a DC beam.

J. Signal Analyzers

1. Spectrum analyzers

Spectrum analyzers are used in the Antiproton Source to study the frequency domain of the beam. A spectrum analyzer is a swept-tune superheterodyne receiver that provides a Cathode Ray Tube (CRT) display of amplitude versus frequency. In the swept tune mode the analyzer can show the individual frequency components of a complex signal. The spectrum analyzer can also be used in a fixed tune or "zero span" mode to provide time domain measurements of a specific frequency much like that of an oscilloscope. Note that a spectrum analyzer does not provide any phase information.

A superheterodyne receiver is a common type of radio receiver that mixes an incoming signal with a locally generated signal. The output consists of a carrier frequency that is equal to the sum or difference between the input signals (but no information is lost). The carrier signal is known as the Intermediate Frequency (IF) signal.

In a spectrum analyzer, the incoming signal is mixed with a programmable Variable Frequency Oscillator (VFO) producing carrier frequencies containing the two original signals and signals at the sum and difference of their frequencies. All but the sum or the difference signals are filtered out. The filter output is the IF signal which can be processed for display. The spectrum analyzer uses the VFO to define the frequencies to be analyzed (center frequency and span) and the sample rate (sweep time, resolution bandwidth).

1. Network analyzers

Network analyzers are used to study transfer or impedance characteristics of systems. A reference signal is injected into a system under test and the output of the system is displayed on a CRT (see figure 7.9). Although less expensive analyzers only provide frequency and amplitude information, the network analyzers used in the Antiproton Source also provide phase information. Examples of systems that can be analyzed are coaxial cables, stochastic cooling systems, RF amplifiers and other electronic devices.

Operationally, network analyzers are most frequently used for making transfer function measurements of portions of the stochastic cooling systems. Measurements are said to be either "open loop" or "closed loop". In an open loop measurement, the network analyzer is switched into the stochastic cooling system so that the cooling system is not actually operating (the feedback loop is open). The network analyzer is used to measure how that part of the cooling system (possibly plus the beam) modified the reference signal. In a closed loop measurement, the reference signal from the network analyzer is injected into the operating cooling system (with the feedback loop closed) and a diagnostic beam pickup is used to measure the signal’s effect on the beam. An applications program is used to set parameters and manipulate switches for stochastic cooling measurements.

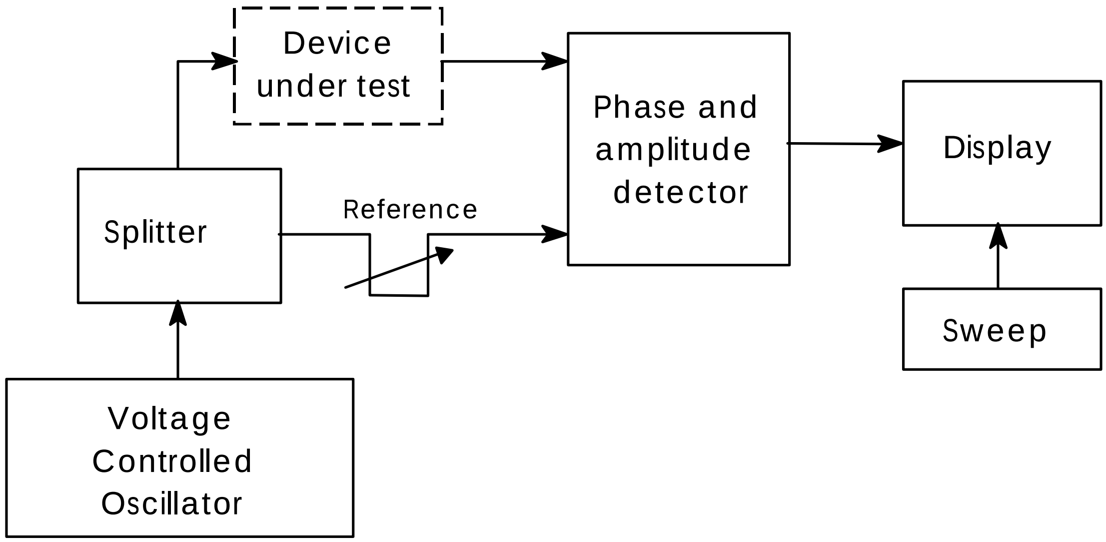

Figure 7.9 Network Analyzer

3. Dynamic Signal Analyzer

The Dynamic Signal Analyzer (DSA) is in many ways similar to a spectrum analyzer. The most noteworthy difference is the DSA's ability to produce a Fast Fourier Transform (FFT) which requires an "on-board" microprocessor. Unlike the spectrum analyzer that sweeps through a frequency range, the DSA has parallel filters, which allow simultaneous measurements across a frequency range. The disadvantage is that the DSA has a limited bandwidth over which it can produce an FFT, defined by the sample rate of the input data.

The DSA's are well suited for their use with the Pbar source's FFT because the longitudinal beam profile being measured in the Debuncher and on the Accumulator injection orbit don't significantly change frequency and have a relatively narrow frequency spread. In the original configuration, an "FFT box" was connected to a pair of spectrum analyzers and did the FFT calculations as well as providing gating for the analyzers. The spectrum analyzers were later replaced with a pair of DSA's, which do the FFT calculation. The FFT box is still used but now only provides trigger timing.

4. Vector Signal Analyzer

The Vector Signal Analyzer (VSA) is a hybrid between a DSA and a spectrum analyzer in the sense that it combines the power of digital signal processing of the DSA with the enormous frequency range and dynamic range found in a swept tune instrument. This new generation instrument attains this "hybridization" with a large parallel digital filter array at its input and, more importantly, the improvements in chip technology. The VSA has a much larger bandwidth than the DSA. The VSA could make a similar measurement for signals that changed frequency or had a large frequency spread. The VSA was developed to meet the demand for an instrument capable of measuring rapidly time-varying signals and to address problems dealing with complex modulated signals that can't be defined in terms of simple AM, FM, RF, etc.

Spectrum analyzers work very well for signals that don't vary over time, but are difficult to use in situations where the opposite is true. The Accumulator momentum profile typically displayed on CATV Pbar channel 29 provides a good "snapshot" of what the beam looks like shortly after ARF-1 has moved beam to the edge of the stacktail. It is not a true snapshot due to the fact that there is a finite sweep time required to measure the signal. The signal being displayed on the low frequency side of the analyzer is sampled at a time earlier than those on the high frequency side. If one wanted to examine what took place at other times in a typical stacking cycle, the spectrum analyzer would need to be triggered at different times, although the problems related to the finite sweep time would still exist. The VSA could input the same signal and create a continuous display of the beam movement during the stacking cycle. While the spectrum analyzer could create the equivalent of sets of overlapping still photographs, the VSA would create a movie. The VSA is most frequently used for studies but is available as a diagnostic for operational problems.

K. Resistive Wall Monitor

Circulating beam with a bunch structure causes current to flow on the inside of a metallic beam pipe such as the stainless steel beam pipes used in the Antiproton Source. By breaking the metal beam pipe with an insulating ceramic gap and placing a resistor across the gap, one can measure the voltage drop across the resistor that is proportional to the beam current. There are two wall monitors in the Accumulator located in the 10 and 50 straight sections (the latter was moved from its original location in the AP2 line). The most common use of the Accumulator wall monitors is to observe the bunch structure on the beam. In collider run 1b the A10 wall monitor was used for the ARF3 feed forward system and also used to measure the longitudinal emittance of extracted beam.

The frequency response of the pickup rolls off on the low end because of beam pipe conditions external to the pickup, so the pickup is housed in a shielding box loaded with ferrite material to provide a known value of inductance. The geometry of the ceramic gap and the resistors are chosen to form a properly terminated transmission line. The low frequency response of the wall monitor is determined by the time constant set by the ferrite (16 mH) and the gap resistance (0.5Ω), it is about 5 kHz.

The characteristics of the ferrite inductors also set the high frequency response of the pickup. Two types of ferrites and a coating of microwave absorbing paint inside the shielding box are used to provide an even frequency response to 6 GHz.

As beam passes irregularities, like bellows, in the beam pipe, it induces microwave fields at frequencies determined by the dimensions of the beam pipe structures. That energy travels down the inside of the pipe and can be detected by the wall monitor. To avoid those noise problems, ferrite chokes are installed on both ends of the wall detector.

Signals are taken off the gap at four points around the circumference and summed to minimize sensitivity of the output signal to variations in beam position within the pipe. The overall sensitivity of the monitor, accounting for gap resistance, summing of the four signals, 50Ω terminating resistor, etc. is approximately 0.15Ω. That is, the transfer impedance of the pickup is the output voltage over the beam current:

$$Z_{pu} = \frac{V_{out}}{I_{beam}} = \frac{.15\text{V}}{1\text{A}} = .15\ \Omega$$

L. Dampers

Transverse dampers exist in the Accumulator for the purpose of damping out transverse coherent instabilities (beam wobble) at frequencies lower than that of the transverse stochastic cooling systems (2-4 and 4-8 GHz) and also for use as diagnostic tools. The dampers operate in the frequency range of 240 kHz to 150 MHz and act on much larger beam samples than the stochastic cooling does. The lower limit to the frequency response was selected to include the lowest betatron sideband, which is located at 240 kHz.

The upper frequency limit of the dampers is dictated by the length of the pickup and the response of the amplifiers.

All transverse information about the beam is contained in the betatron sidebands. Since the pickups are located in a low dispersion region, there should be nearly no difference between beam position at the core vs. the injection orbit. It is important for the beam to be centered in the pickups to properly damp out oscillations. The pickups are mounted on motorized stands for centering them with respect to the beam. Signals at harmonics of the revolution frequency contain no useful information for transverse damping. Notch filters are used to reject revolution harmonic signals that could swamp the electronics during pbar extraction.

The dampers consist of pickups and kickers (both horizontal and vertical) located in a low dispersion area. The pickups and kickers are located nearly adjacent to each other, but it is actually the *next* beam turn that is corrected. Since the tune is not far from ¾, the beam at the kicker has oscillated nearly the ideal odd multiple of 90° away from the pickup. The damper kickers apply a correcting force on the beam by deflecting or “kicking” the beam. The pickups are 0.5m long $^1/_4$ wave radial striplines located in the A10 low dispersion straight section to reduce any possible longitudinal coupling. The pickups sense coherent betatron oscillations and the signal passes through an amplification system and an appropriate delay line to match the pickup signal to the transit time of the beam. The amplifiers are able to deliver up to 300W of power (although they normally run at 2W or less) to the 50Ω terminated $^1/_4$ wave kicker loops also located in the A10 straight section.

As a diagnostic the dampers are used to amplify transverse oscillations, or heat the beam, by driving the kickers with a white noise generator. This is useful for performing aperture measurements; beam fills the aperture and a scraper defines the edges of the beam. A reversing switch can be used to connect the damper pickups to a different set of kickers for reverse protons.

There are also dampers in the Debuncher although they are only used for studies and were never intended to be used operationally. The time that beam resides in the Debuncher is short during stacking and the intensity is low, both tend to discourage the growth of transverse instabilities. The lowest betatron sideband in the Debuncher is located at 110 kHz, which requires a different amplifier than those used in the Accumulator. The Debuncher damper system has a useful frequency band of 10 kHz to 12 MHz and a peak power output of about 100W. The Debuncher dampers do not use a notch filter as the Accumulator does.

M. Wide Band pickups

As the name implies, the wide band pickup is able to detect a relatively broadband range of frequencies as compared to other detectors. Actually the resistive wall monitors and gap monitors are also broadband but have poor response that makes it difficult to observe Schottky signals. The wideband pickups, both horizontal and vertical, are actually made up of three small $^1/_4$ wave stripline Schottky detectors. A 10 inch pickup is sensitive to signals in the .2-.4 GHz range, a 4 inch pickup sensitive to signals in the .5-1 GHz range and a 2 inch pickup sensitive to signals in the 1-2 GHz range. Each pickup is attached to hybrids that provide both sum and difference signals for viewing at AP10. All twelve signals (sum and difference signals for three horizontal and three vertical pickups) are connected to amplifiers that must be powered to provide a strong enough signal for the signal analyzers. An analyzer must be connected to the appropriate cable spigot at AP10 to select a particular frequency range, the switch tree can only be used to connect horizontal or vertical set of pickups to the appropriate analyzer.

The wide band pickups are located in the A10 straight section and are used, among other things, as the source of the signals used by the Accumulator emittance monitors. It is especially useful for measuring signals related to stochastic cooling in the 1-2 GHz range (recall that the Schottky pickups are sensitive to frequencies in the 70-80 MHz range).

N. Gap Monitor

A gap monitor is virtually identical in design to a RF cavity. In fact the gap monitor used in the Accumulator in the 10 straight section is the same style resonant cavity used for ARF2 and DRF2. Unlike a RF cavity, which has power applied to it to accelerate or decelerate the beam, as bunched beam passes through the gap in the cavity a voltage is produced.

The gap monitor is not a totally passive device, the beam is decelerated slightly as it passes through the gap (what would be the accelerating gap in a RF cavity). The amount of energy given up by the beam as it passes through the resonant cavity is determined in part by the Q of the cavity (the relative strength of the resonance). The gap monitor cavities are intentionally lower in Q than the RF cavities. The low Q weakens the signals but reduces the effect on the beam. Although the cavities retain the ferrites used in RF applications, the capacitance is kept much lower. The gap monitor is a relatively large bandwidth device but is not sensitive enough to detect Schottky signals.

O. Flying wires

Six flying wires are used in the Accumulator to allow accurate transverse emittance and momentum distribution measurements. Five of the wires are located in a single assembly in the A40 high dispersion straight while the other wire is located in A30 between A3Q7 and A3B7 where the dispersion is relatively low. The three horizontal wires in A40 are positioned to allow separate measurements of beam on the injection orbit, central orbit and core orbit.

Each flying wire is a 25 micron carbon fiber which is held in a fork

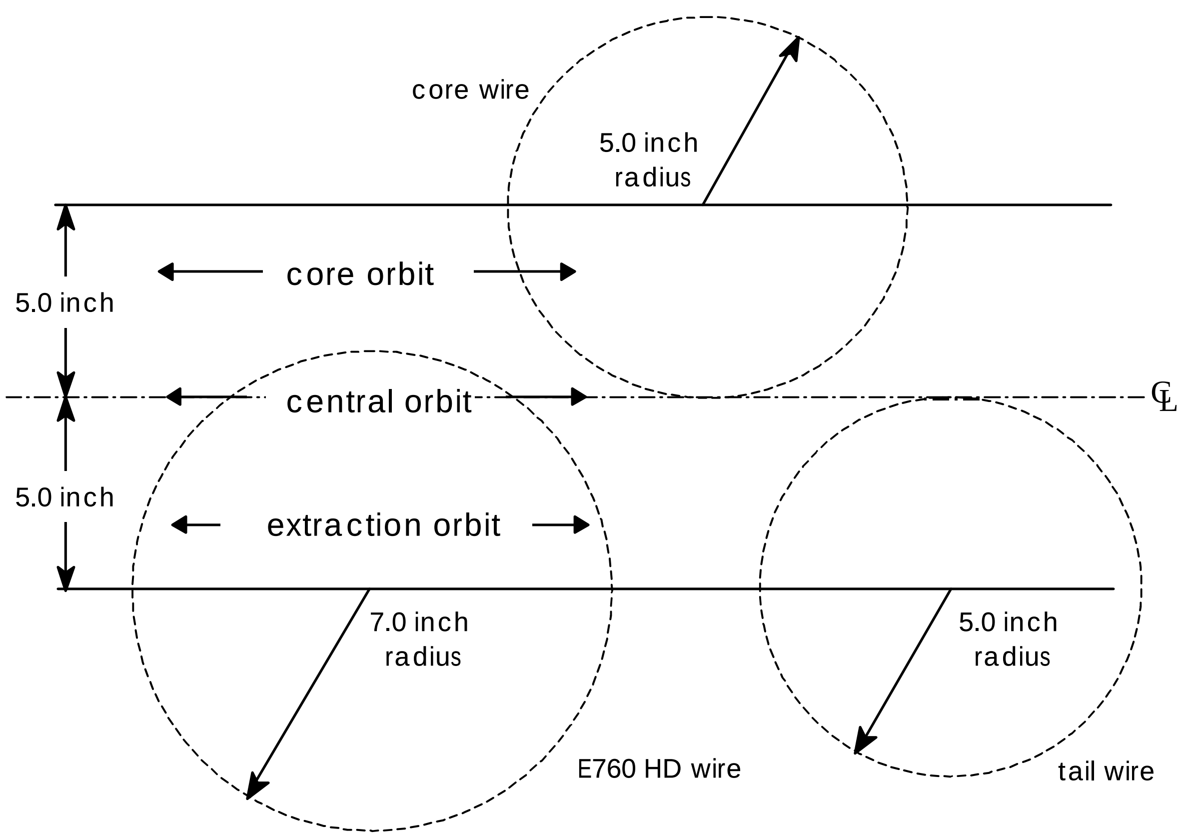

Figure 7.10 A40 high dispersion straight flying wires

assembly and passed at velocities up to 10 m/s through the beam. The wire passing through the beam creates a cascade of losses that is proportional to the beam intensity at that wire position. A paddle made of plastic scintillator is placed downstream of the wire to intercept part of the secondaries (actually there are paddles on either side of the flying wire for both proton and antiproton beams). Particles passing through the scintillator produce light that is measured with a Photo Multiplier Tube (PMT). The PMT produces a signal that is proportional to the secondaries passing through the scintillator paddle. An optical encoder on the flying wire assembly provides position information to an angular resolution of 0.022 degrees. Using the PMT output and the wire position information a beam profile can be created.

Of the five wires located in the A40 straight section there are core horizontal and vertical wires, tail horizontal and vertical wires (actually mainly used for the injection/extraction orbit), and the E760 high dispersion (horizontal) wire (for the stacktail and central orbit). By comparing beam profiles from the E760 high dispersion wire and the A30 low dispersion wire, the momentum distribution can be inferred. Figure 7.10 provides a view from above of the three horizontal wires in the A40 wire assembly.

Flying wire system hardware is located at the south end of the AP30 service building. The system is built around a Macintosh computer, which is connected to the ethernet. Motion control is supplied by a pair of NuLogic 3-axis motor controllers. A VME-based system (see figure 7.11) is used for data acquisition, the VME modules are mostly Fermilab design including clock decoders, trigger modules, digitizers and scalar cards. The flying wire software is a LabVIEW application running on the Macintosh. Communication with the computer requires either manual operation at the computer, logging in from another Macintosh or logging in from a terminal via Telnet. ACNET application program W64 is used for manipulating flying wire data and there are ACNET parameters that provide measurement and timing information.

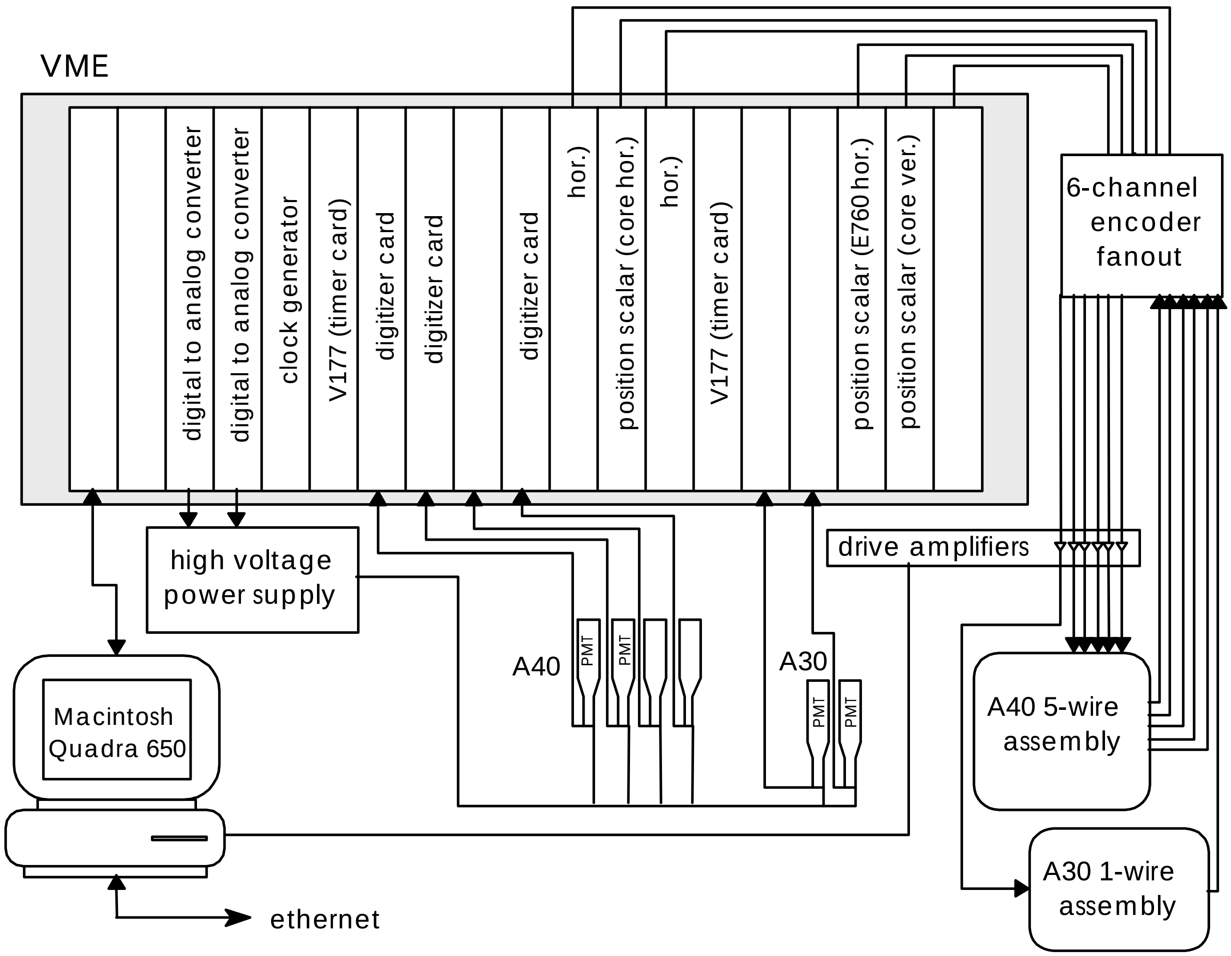

Figure 7.11 Flying wire system hardware

P. Clearing Electrodes/trapped ions

There are about 140 clearing electrodes located at various points in the Accumulator. The clearing electrodes are used to reduce the number of positive ions that are trapped in the beam. Before going into detail about the electrodes themselves, a short discussion about the trapped ions and their interaction with the antiproton beam will follow.

Residual gas in the Accumulator vacuum chamber that passes through the antiproton beam can have an electron stripped away, leaving a positive ion. The positive ions are being continuously produced as long as the antiproton beam is present. The production rate depends on the quantity and type of residual gas in the vacuum chamber as well as the beam intensity. A typical rate would be on the order of 10 E10 to 20 E10 per second for a 40

E10 stack. In the absence of any outside influence, the number of positive ions will increase until the antiproton beam is totally neutralized.

The production process results in the ions having a small velocity and nearly all of the ions that are produced become trapped in space charge potential wells. The depth of the wells depends on the size of the beam pipe and the size of the beam envelope at a particular location. The ions will move longitudinally towards the deepest potential well that they can reach. The ions oscillate transversely in the antiproton beam, their frequency dictated, in part, by the mass and charge of the particular ion and the depth of the beam space charge potential well. About half of the ions produced are monatomic and molecular hydrogen that have lost an electron (the hydrogen outgasses from the beampipe). The oscillation frequency of the hydrogen ions happens to be close to the low order betatron resonant frequency of the beam and will therefore drive coherent oscillations of the beam. It is interesting to note that a proton (or positron) beam also creates positive ions, but they are not attracted to the beam and do not become trapped as they do with an antiproton (or electron) beam.

The net effect of having the trapped ions in the Accumulator is that the beam is very sensitive to instabilities that are driven by these ions. There is a threshold at which the combination of transverse and longitudinal beam size will result in rapid transverse emittance growth of the beam. Several colorful names, such as "motorboating" and "porpoising" have been given to this rapid growth of emittance, which often is periodic over about 30 minutes. Since the transfer efficiency of Pbar shots to the Main Ring improves as emittances are reduced the trapped ions can lead to reduced luminosity for the collider experiments. Trapped ions have another detrimental effect, which is a tune shift for the antiproton beam. This is easier to compensate for as the shift will normally be nearly constant.

The most successful strategy for mitigating problems relating to trapped ions has been to eliminate as many of the ions as possible. It is necessary to constantly remove the trapped ions as they are continuously produced and over seconds will return to fill the potential wells. The greatest reduction in trapped ions has come from the use of clearing electrodes. Originally the clearing electrodes were a few select Beam Position Monitor pick-ups which had a -100 Volt potential applied to them. An upgrade was put in place in Collider run 1a which included expanding the number of clearing electrodes and increasing the potential to –1,000 Volts. Dedicated clearing electrodes were added to locations such as stochastic cooling tanks, which did not have BPM's in close enough proximity.

There are still locations, such as in the middle of the bending magnets, where a clearing electrode cannot be located. Another method for dislodging the trapped ions is bunching the beam with RF. Only 10-20 volts of RF is enough to significantly reduce the population of trapped ions in the Accumulator, additional RF provides little additional benefit. By bunching the beam some of the trapped ions can be flushed from the potential wells they reside in. The ions that are dislodged appear to be forced into the vacuum chamber walls instead of being pushed towards the clearing electrodes for removal. It is believed that the clearing RF is not as effective for clearing heavy ions, which means that some of the cleared hydrogen atoms will be replaced by the heavier, less harmful ions. If the stabilizing RF is removed, it may take several minutes for the trapped hydrogen ions to return to the equilibrium level maintained in the absence of the RF. ARF-2 has traditionally been used to provide the "stabilizing RF" for the Accumulator.

The combination of clearing electrodes and stabilizing RF has resulted in a lower critical threshold of emittances for ion induced instabilities. This threshold is lower than the cooling systems can achieve for even the largest stack sizes to date. Smaller emittances and momentum spread have allowed efficient transfers to be made to the Main Ring with stacks in the 200 E10 range.

Q. Quadrupole Pick up

The quadrupole pick up is located in the Accumulator at the upstream end of the A10 straight section and is used to measure transverse quadrupole oscillations of the beam. There is also a skew-quadrupole pickup located next to the "normal" quad pick up but it has been rarely used. The pickups are about a meter in length and are made up of four striplines. The quad pick up has the striplines oriented vertically and horizontally on either side of the beam, the skew quad pick up has the striplines rotated 45°. The signals are amplified then sent to electronics in the AP-10 service building, which processes the signals. Vertical, horizontal, sum and quadrupole signals are available for use.

Unlike dipole oscillations, which arise from steering errors, quadrupole oscillations are the result of lattice (ß function) mismatches between an accelerator and associated beamline. Typically the quad pick up would be connected with a digital oscilloscope to view the signal. The primary use of the pick up to this point has been to attempt to quantify the lattice mismatch between the AP-3 line and the Accumulator. In principal, the match can be improved by varying AP-3 quadrupole currents and observing and minimizing the amplitude of the quadrupole oscillations from protons reverse-injected from the Main Ring. In practice the quadrupole signals are swamped by the dipole signals. The pick up could be used to detect quadrupole instability signals or work as a quadrupole damper, but it's not presently set up that way.

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VIII. Utilities

A. Water systems

Water is commonly used as the medium for carrying excess heat away from power supplies and their loads in the Antiproton source. The most extensive water system found in Pbar is the 95° Low Conductivity Water (LCW) system which provides cooling for components in the Rings and Transport enclosures as well as the AP0, 10, 30 and 50 service buildings. LCW is water which has had free ions removed, increasing its resistance to electrical current. This attribute is critical if a device has cooling channels that also act as electrical conductors. Most rings and beamline magnets, for example, have hollow copper electrical windings that the LCW flows through. The Pbar 95° LCW system is not only used to cool most magnets and their power supplies, but also magnet shunts and TWT amplifiers used in the stochastic cooling systems.

The two heat exchangers, three pumps, de-ionizing (DI) equipment, deoxygenation skid and makeup reservoir for this system can all be found on the second floor (frequently referred to as the mezzanine) of the Central Utility Building (CUB). During normal operation, two of the three pumps are run which allows flexibility if a pump requires repair. Water flows through the deoxygenation skid and removes oxygen from the LCW that could combine with Copper to form CuO. Depending on the season, the LCW will pass through one or both of the two heat exchangers (both housed in a signal unit). The LCW heat exchanges with industrial water (also known as pond water) which originates from the Booster pond. The pond water passes through the base of CUB into the cooling water vault on the northeast corner of the building. After passing through a set of strainers the pond water is pumped to the various heat exchangers by four vertical pumps. During the warm weather months, when the pond water temperature is too high to provide sufficient (if any) cooling, the cooling towers atop CUB provide a supplemental drop in the temperature of the pond water before it passes through the heat exchangers. The cooling towers are like an automobile radiator in function but augmented by pond water flowing over the outside of the cooling fins to provide an additional temperature drop resulting from the latent heat of evaporation.

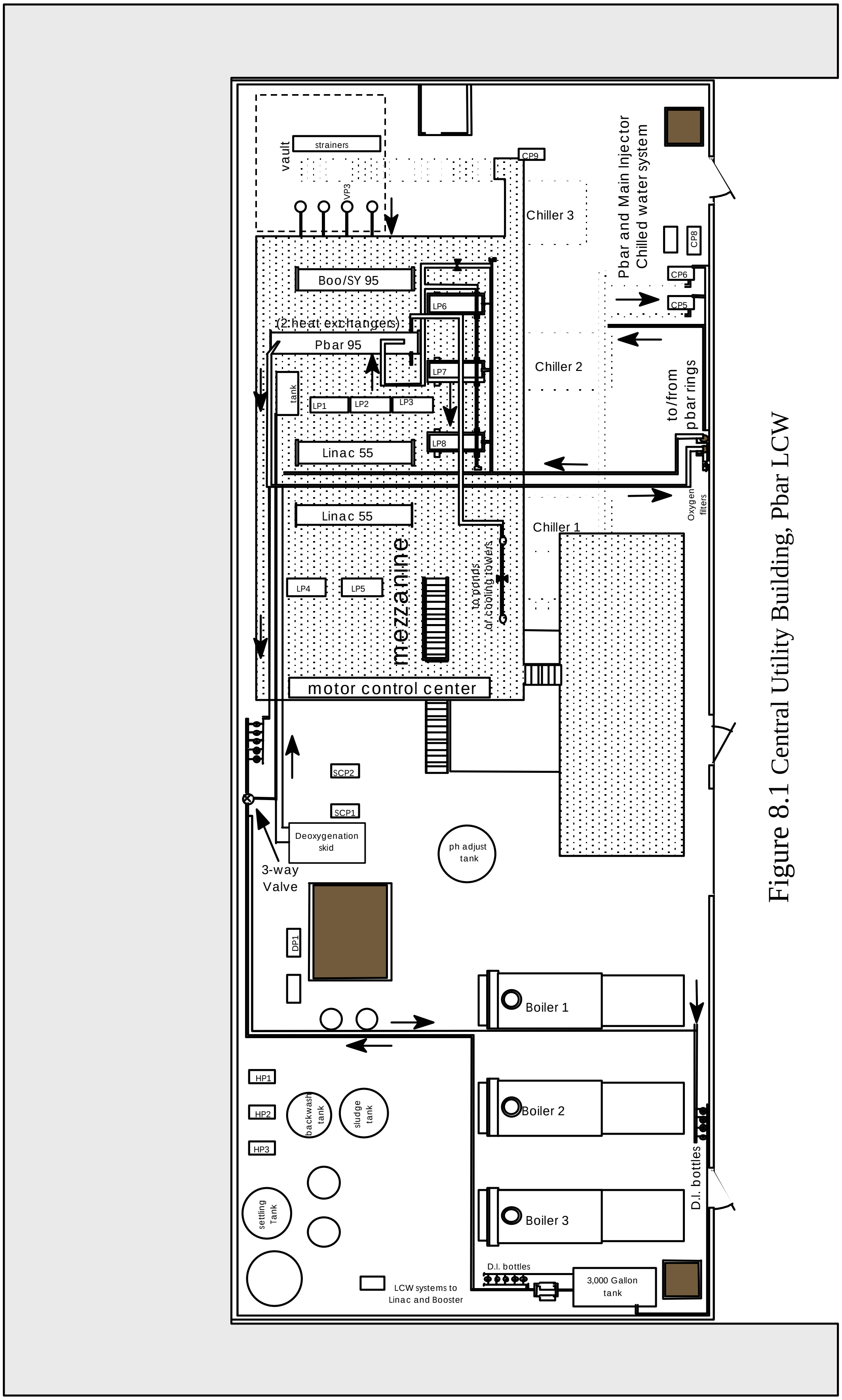

Figure 8.1 Central Utility Building, Pbar LCW

After water has returned from the heat loads in the tunnels and service buildings, it passes through one of two large “full-flow” filters in CUB. The primary motivation for adding this filter system, as well as the deoxygenation equipment already mentioned, is to minimize the production of CuO. Deposits of this copper oxide can line the inside of the magnet conductors and even cause blockages. The restricted water flow and insulated cooling channels results in elevated temperatures in the magnet. In extreme cases the magnet epoxy can be damaged and may lead to a magnet failure. A floor plan of CUB is provided in figure 8.1, which may be helpful in locating components of the LCW system.

The Chilled Water (CW) system, provides cooling water for the service building air conditioning units, the DRF1 cavities, and the stochastic cooling kicker tanks. It also removes heat from the closed loop LCW systems at AP0 and F27, which are described below. CW is pond water, which has been strained and chilled to approximately 48° Fahrenheit. The CW system is sometimes incorrectly referred to as the industrial chilled water system. This name tends to confuse CUB personnel as they use the CW designation for chilled water while referring to water in the fire hydrant network as Industrial Cold Water (ICW).

Tevatron 95° LCW flows through the AP1 and AP3 line magnets in the Pretarget and Prevault enclosures. Tevatron LCW is also used to cool power supplies at the F23 service building. LCW from the Tevatron system was used for reasons of convenience and economy.

Five closed loop, stand-alone LCW systems can be found at the perimeter of the Pbar complex. Each of these systems consist of a pump, heat exchanger, deionizer bottle, expansion tank, and associated plumbing and instrumentation, similar to the Linac water systems. CW is used to heat exchange with each closed loop LCW system. Four of the systems are located in AP0: one provides cooling for the collection lens, one for the beam dump, another for the pulsed magnet and a fourth for the proton lens. When needed, make up water to fill these systems is taken manually from the Pbar 95° LCW header nearby by target station technicians.

The other closed loop system is located at F27 and services the power supplies in that building. No LCW lines pass in the vicinity of the F27 building, hence the need for a separate system. When required, LCW at F27 is made up by the water group personnel from a 55-gallon drum of de-ionized water. As stated above, CW is the heat exchanging medium and gets to F27 and AP0 by means of teeing off of the line which runs between CUB the RF building.

Important parameters of the water systems are monitored via ACNET and/or FIRUS. Temperature, pressure, oxygen level, turbidity and conductivity monitoring for the Pbar 95° LCW system can be found on page P75, a graphical display is also available on P74. Temperature and pressure readbacks for the chilled and pond (cooling) water loops can also be viewed from P75. In addition, the amount of water leaking out of the Pbar LCW system can be determined through the ACNET parameter D:LCWTOT. This device reads back the total amount of water made up over an arbitrary amount of time. The Pbar 95° LCW system has a 30 gallon reservoir which is filled up every time that amount of LCW has leaked out of the system. Under normal no-leak running conditions, 0 to 30 gallons per week is added to the system. A plot of D:LCWTOT would indicate 30 gallon increments at regular intervals if there were a leak (this parameter is reset to 0 gallons every day at midnight). D:LCWMUF monitors the flow into the makeup tank and normally reads zero. Only when the LCW system is automatically filling the 30-gallon reservoir should this parameter have a non-zero reading.

FIRUS also alarms if certain parameters are out of limits. In general, poor conductivity, incorrect pressures or tripped chillers or cooling towers should be brought to the attention of on-shift plant maintenance personnel i.e. the Duty Mechanic. Pressure or temperature alarms should be checked against their ACNET counterparts. Generally, the ACNET devices have more accurate alarm set points.

B. Vacuum systems

All of the beam lines and both rings are unique vacuum systems isolated from each other via vacuum windows (with the exception of the Accumulator to AP3 line connection). In all cases, distributed ion pumps provide most of the pumping and the vacuum chamber is broken into smaller segments with beam valves. A number of pump-out ports are built into the system to provide easy connection of mobile turbomolecular pump stations. Tevatron-style CIA crates are used to control the vacuum components. Beam valves are interlocked to close if three or more ion pumps in a section are tripped or indicate poor vacuum. Each system is outlined below. For the sake of clarification, Torr is normally the unit of measure used as a measure of vacuum although millibar (mbar) is the proper metric unit. The units are very similar in magnitude, average atmospheric pressure is 760 torr or 1,013 mb. Since the units are so close in magnitude, Torr and mbar's can be used interchangeably.

Vacuum in the AP1 line is common to that of the Main Ring at F1 on the upstream end and AP3 on the downstream end. Beam valve M:BV100, located immediately downstream of the second (of two) 'C' magnets in that beam line, is interlocked to close if too many pumps trip in either the Main Ring or AP1. A vacuum window just inside of the target vault isolates AP1 from the target station. Beam Valve D:BV926 can isolate AP1 from AP3. The nominal AP1 line pressure of 10^{-8} mbar is maintained by distributed sputter ion pumps rated at 270 liters/second. Pump supplies and controls hardware for this system can be found in the AP0 building.

The target vault has no vacuum and serves as the break between AP1 and AP2 vacuum. Another window within the target vault isolates this line at its upstream end. AP2 vacuum is continuous to a window immediately upstream of the Debuncher injection septum magnet. Like AP1, the injection line vacuum is maintained through the use of distributed sputter ion pumps rated at 270 l/s. The nominal pressure of the beamline is 10^{-8} mbar.

The Debuncher, similarly, has its vacuum maintained with sputter ion pumps. The average Debuncher pressure is also 10^{-9} mbar. Beam valves at each '10' location can effectively subdivide the Debuncher into 6 separate vacuum sectors. Beam valve D:BV610 doubles as the safety system coasting beam stop for the Debuncher.

The D to A line is a stand alone vacuum system, the breaks being vacuum windows at the upstream end of the Debuncher injection septum magnet and the downstream end of the second Accumulator injection septum. Ion pumps keep this line's vacuum in the 10^{-8} mbar range.

Because the Accumulator was designed as a storage ring, its vacuum requirements are the most stringent. One of the significant terms in determining the beam lifetime in a storage ring is the beam-gas interaction rate. Improving the vacuum lowers this interaction rate thereby reducing beam loss. The design pressure of the Accumulator is 3 X 10^{-10} Torr. This level is accomplished through the use of sputter ion pumps and titanium sublimation pumps supplemented by a bake-out system. As with the

Debuncher, the Accumulator effectively has six vacuum sections. Beam valves in sectors 10 through 30 and 60 are found at the '7' locations. The valves for the 40 and 50 regions were moved from their original location to immediately upstream and downstream respectively of straight section 50. This provides isolation for the E835 hydrogen gas jet target and associated vacuum equipment with minimal impact on the Accumulator. This results in the Accumulator 40 and 50 vacuum section being larger than the others. Like D:BV610 in the Debuncher, beam valve A:BV607 acts as the safety system coasting beam stop for the Accumulator.

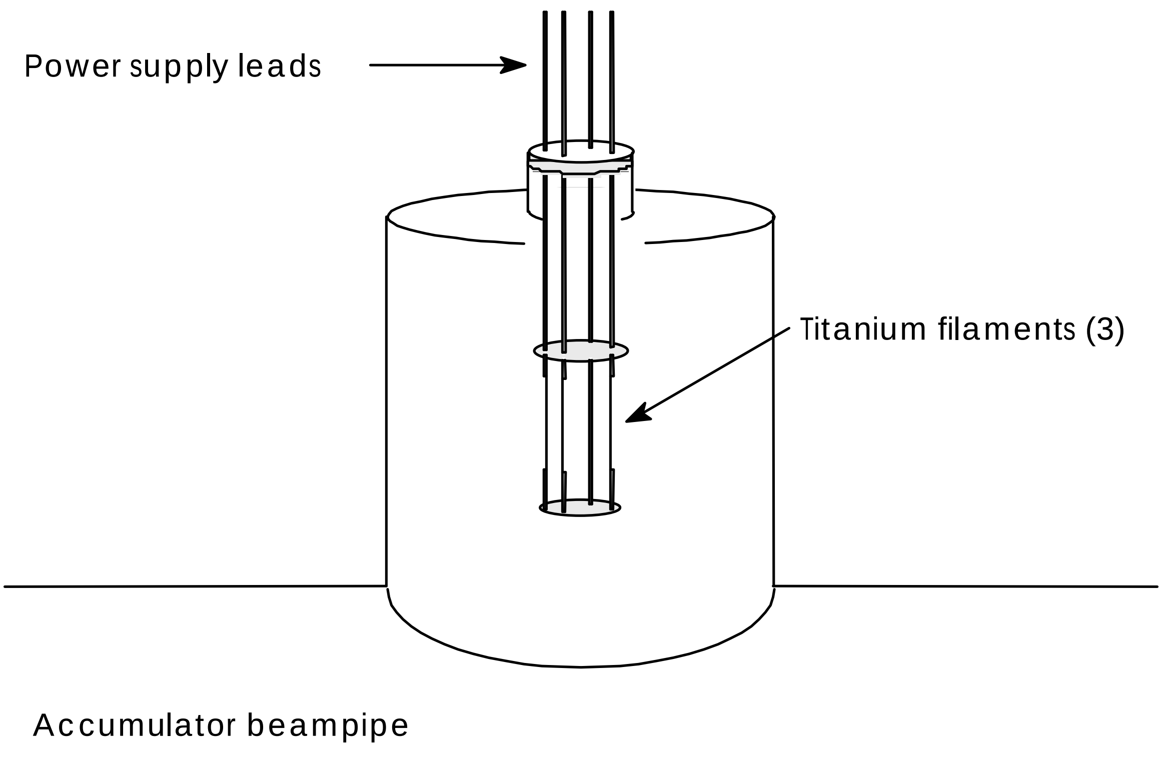

Figure 8.2 Titanium sublimation pump

Titanium sublimation pumps are used for both the Accumulator and Recycler rings. The sublimation pumps are necessary to maintain the low vacuum required for both storage rings. Sublimation pumps are a form of getter pump which operate on the principle that chemically stable compounds are formed between gas molecules (H_2, N_2, O_2, CO, CO_2) and the getter (titanium). In this context, a getter is the material that gas molecules combine with to form stable compounds. Noble gases (such as helium) cannot be pumped by getters. A filament containing a high titanium content is heated resistively, the boiled off titanium forming a thin layer on the surrounding walls. For the Accumulator, the walls are adjacent to the beam pipe rather than being the beam pipe itself. As gas molecules impinge on the getter film, stable compounds are formed and the vacuum pressure improves since there are fewer gas molecules in the beam pipe volume.

Unlike ion pumps which are powered all of the time, the sublimation pumps in the Accumulator are powered infrequently. The sublimation pumps are "fired" over 90 seconds to sublimate approximately 10 monolayers of titanium onto the pump's interior surface. During normal operation, sublimations are spaced months apart. Each Accumulator sublimation pump contains 3 filaments to extend the lifetime of the pump, although only one filament at a time is sublimated (see figure 8.2). Because such pumps have no effect on inert gases, sputter ion pumps are still an integral factor in keeping the Accumulator vacuum at its best achievable level. To date, the best average vacuum in the Accumulator has been 6.8 x 10^{-11} Torr (as read by ion guages); a typical value is 1.5 x 10^{-10} Torr.

A permanently installed bake-out system in the Accumulator makes it possible to bake each of the six sectors independently when conditions warrant. Usually when a portion of the Accumulator is let up to air, for installation of new diagnostics for example, a bake-out follows the work. Baking the beam pipe makes it possible to remove water vapor on the inner surface of the beam pipe and remove deep-seated impurities. Bake-out temperatures range from 130° C for stochastic cooling tanks to 250° C for quadrupoles. Pumping during a bake is by means of mobile turbomolecular pump carts. The bake is controlled by a single microprocessor in AP10 while an ACNET applications program exists for human interface. The processor receives inputs from thermocouples located in the tunnel and controls heaters to regulate the temperature. It typically requires several days to heat the components to the desired temperature, bake, then slowly cool back down to room temperature. Heaters and insulation coexist in the blankets, which are wrapped around the beam pipe and non-magnetic components. The magnets are not encased in blankets, rather, special channels for LCW together with heating elements are sandwiched between the beam pipe and magnets proper (see figure 8.3). Such an arrangement permits the beam pipe to be baked while minimal heat is imparted to the magnets.

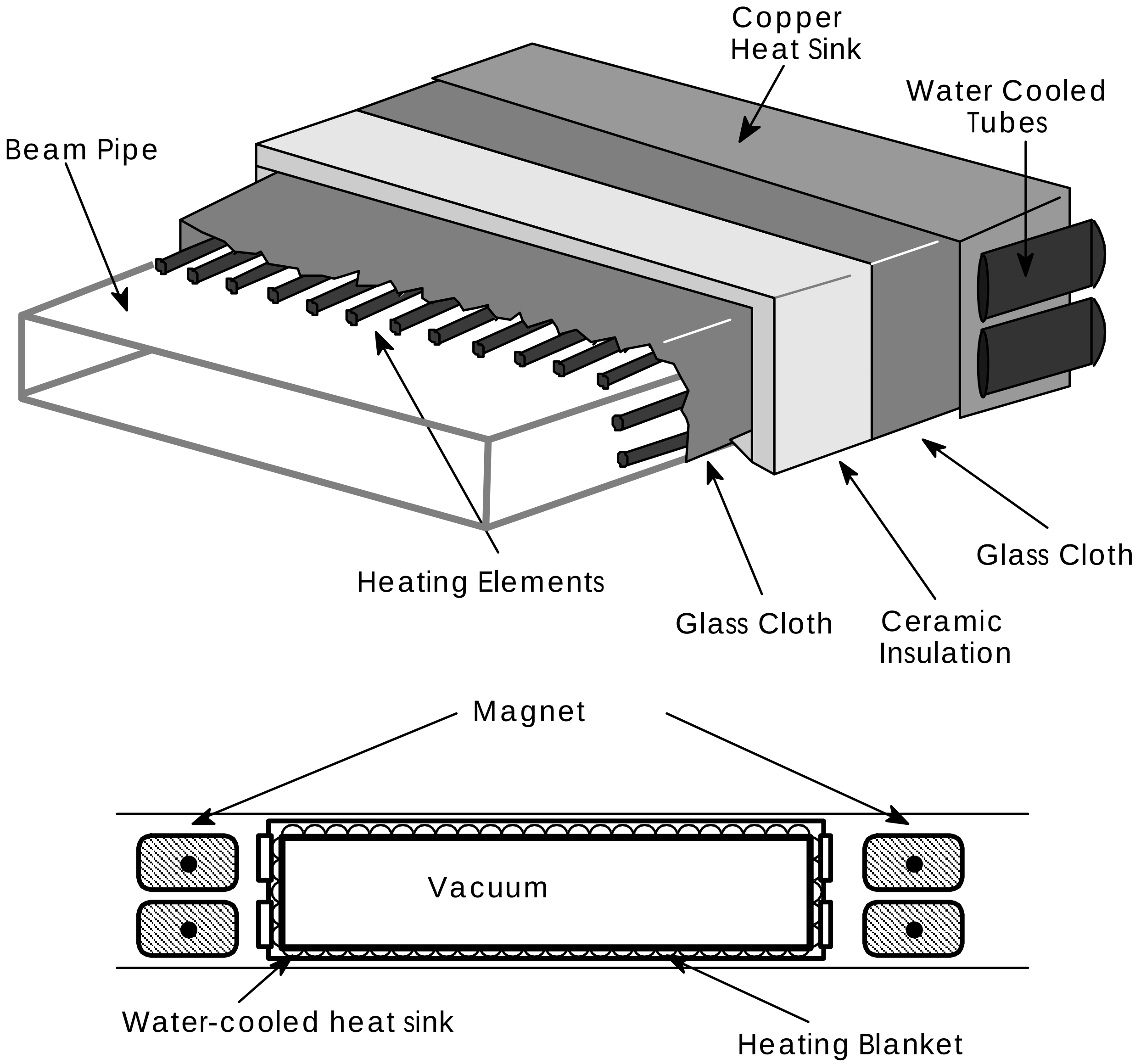

Figure 8.3 Accumulator dipole bakeout cross-section

The AP3 line vacuum is common to the Accumulator due to the concern that a vacuum window at the junction of the Accumulator and the beam line would cause unwanted transverse emittance blowup during beam transfer. Despite the absence of a vacuum window, Accumulator vacuum does not degrade significantly near the junction. A beam valve, BV900, provides protection in case of loss of vacuum in either the Accumulator or AP3 line.

Vacuum is maintained in AP3 again with 270 l/s sputter ion pumps. The pressure is typically 10^{-8} mbar. Beam valve D:BV926 located in the Prevault enclosure provides isolation between the AP1 and AP3 lines.

C. Electrical systems

Power requirements for most of the Antiproton source complex is provided by feeder 24, a 13.8 kV feeder, which is the output of transformer 83A in the Master Substation. 13.8 kV is stepped down to 480 V in substations outside of AP0, 10, 30, 50, and F27. Breaker panels and additional transformers distribute power to all tunnel and house loads as well as nearly every power supply. The Debuncher and Accumulator bend bus supplies have separate

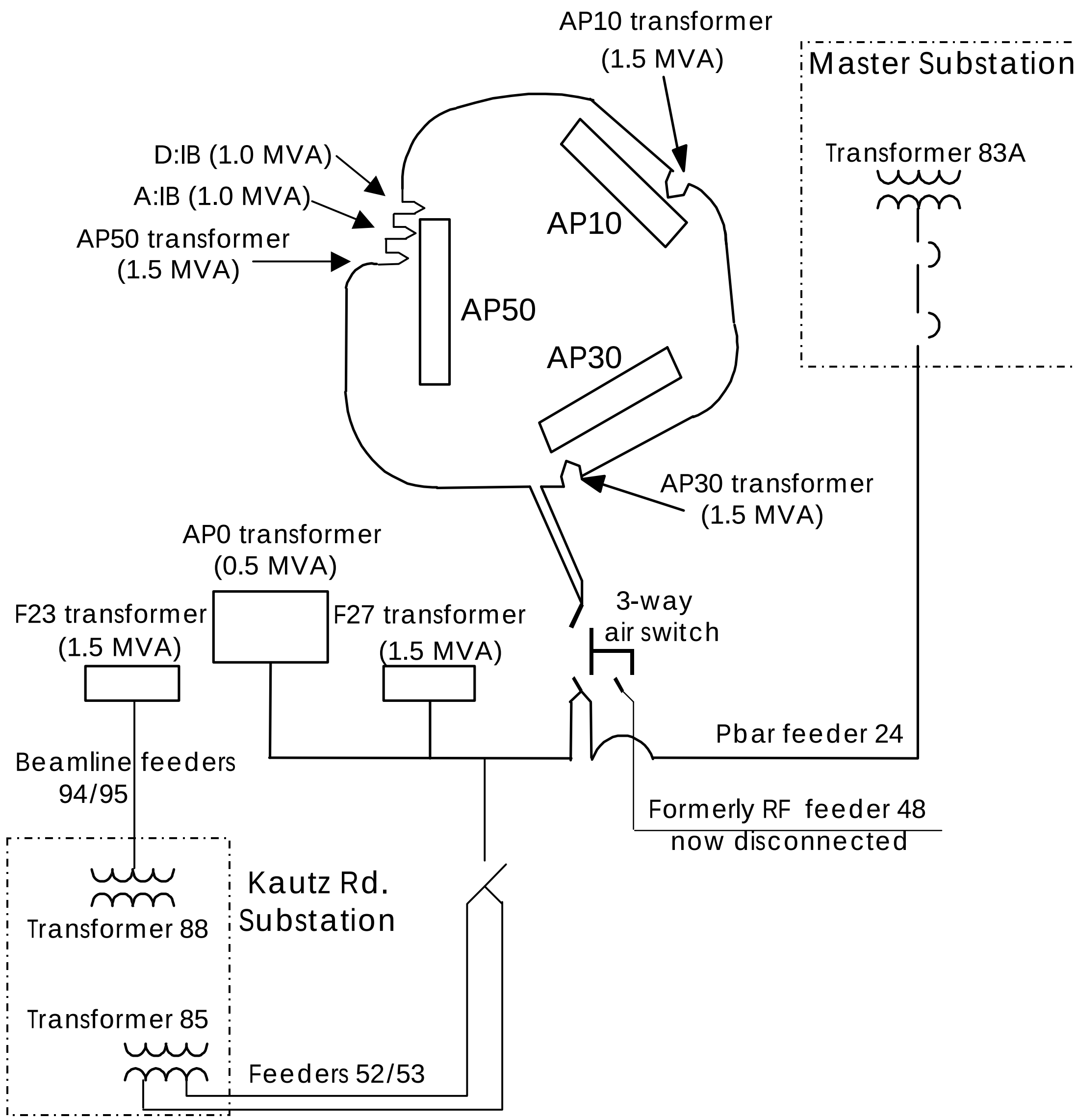

Figure 8.4 Antiproton source 13.8 kV feeder layout

outdoor transformers connected to feeder 24 at AP50 (see figure 8.4). Power for the AP1 line supplies, which are located at F23, comes from feeders 94/95, the beamline feeders. Also, some of the racks in the F27 service building are powered by a line from the F2 service building, which is connected to feeders 94/95. The source can be powered by feeder 52/53, which powers Main Injector service buildings, by means of a transfer switch. This is not done during normal operation due that feeder's relative 'noisiness'. Normally, feeder 24's sole load (and transformer 83A) is the Pbar source.

In case of a power outage, an emergency diesel generator located at AP50 keeps Pbar source sump pumps, ventilation equipment, and the overhead crane in AP0 operational. If normal power is sensed to be absent at AP0, 10, 30, or 50 the generator is automatically turned on and the emergency feeder energized. Meanwhile, a transfer switch in or below the building(s) sensed to be without power switches in the emergency feeder. The generator is automatically tested every week. Controls for the generator is located at AP0.

D. Cryogenic systems

Liquid helium is used to cool the pickup electrodes and GaAsFET amplifiers of the Debuncher betatron and momentum systems. Similarly, liquid nitrogen is used on pickups for the stacktail and core 2-4 GHz momentum cooling systems. By reducing the temperature of these components, the electronic noise they generate is greatly reduced. Electronic noise scales linearly with absolute temperature so there is a considerable reduction in the noise level. This is primarily a concern with the stacktail and Debuncher cooling systems, which operate on low intensity beams. Pickups for the core systems detect a much larger signal due to the larger beam intensity. The core 2-4 GHz momentum cooling system makes use of liquid nitrogen only because the pickup tank is located in A20 next to the stacktail pickups. Performance of the system is only improved by a small amount, but little additional hardware was required to provide liquid nitrogen to the tank.

Cryogenics are provided to these areas by means of transfer lines traveling above ground from AP30 to the D10 and A60 regions, thence through penetrations into the tunnel. AP30 houses a satellite refrigerator once used to provide liquid helium to fill three dewars which contained stacktail momentum cooling notch filter components. This refrigerator is now relegated to a test set up for the Cryogenics department. The AP30 refrigerator is connected to the Tevatron cryogenic system via helium and nitrogen lines between it and the F3 refrigerator building.

E835 uses liquid nitrogen for a cold trap for the gas jet target. A flexible hose transfer line inside of the Rings enclosure transports lN_2 from A60 to the A50 straight section. The experiment also has a "stand alone" helium system housed in the AP50 service building. Helium is transferred through a buried pipe between AP30 and AP50. After passing through the refrigerator in the AP50 service building, the helium passes downward to a cryostat in the A50 experimental pit. The helium is used to reduce electronic noise on the E835 VLPC (Visible Light Projection Chamber).

Control for the majority of the pbar cryogenic systems is identical to that of the Tevatron and Switchyard refrigerators. The house names for the three microprocessors servicing Pbar are: 'PR' for the Pbar Refrigerator equipment at AP30, 'P1' for the area 10 and 60 loops, and 'P3' for the lines leading to the lHe dewars at AP30 that are no longer used. Feedback loops manipulate valves to control each stochastic cooling tank's temperature. The helium system in AP-50 was developed by the old Research Division and uses a different controls interface.

E. Controls system

As with other accelerators on site, the pbar source is controlled and monitored from the Main Control Room via ACNET consoles which send and receive information by means of the Accelerator Division's VAX cluster, known as ALMOND, and the Pbar VME type front end computer. A dedicated serial link connects all of the service buildings, including F23 and F27, with the Pbar front end. In actuality there are six serial loops: PIOX, TCLK, PIOR BTR, MRBS, Pbar Beam Permit Loop, and a link for remote ACNET consoles.

The pbar CAMAC link is connected within and between service buildings with repeaters (figure 8.5 shows the layout of the crates and repeaters in the service buildings). An Applications program currently residing on D20 visually displays the status of the link and the contents of each crate. The pbar controls system is unique in the number of diagnostic devices such as spectrum analyzers, which can be controlled and displayed remotely. This is made possible through the use of the GPIB protocol. GPIB is an acronym for

General Purpose Interface Bus and is based on HPIB developed by Hewlett-Packard.

Crates are numbered according to the service building they are located in. AP10 houses the $1n crates, the 30 and 50 houses contain the $3n and $5n crates respectively. Crates $70 through $74 are located in AP0, $80-$82 in F23, and $90 and $91 in F27 (see figure 8.5). Not all pbar source devices are controlled through the pbar front end, it is sometimes more convenient to control devices from nearby CAMAC crates attached to a different front end. For example, pbar LCW parameters from CUB are read back through the Booster front-end.

The source has a dedicated beam permit/abort loop. The Pbar Beam Permit Loop is a serial loop of CAMAC 200 modules which is sourced in the MCR back racks in a unique 201 card. The 201 sends out a 5 MHz signal, which, if each 200 module has no faults, is passed along and returned to the 201. If one of the eight inputs to a 200 module is low, the 5 MHz signal is not passed along and the loop collapses. There is no beam dump in the Rings into which beam can be aborted. The Beam Switch Sum Box (BSSB) in the Main Control Room will not allow beam to Pbar if the permit is down. The Main Injector Beam Synch (MIBS) event associated with extraction from the Main Injector to pbar will also be disabled if the pbar permit is down. Only a limited number of devices will pull down the permit loop. These inputs included the Rings and Transport radiation safety systems, E835 radiation monitors, the F17 Lambertson power supplies and a summation of radiation monitors (chipmunks) located in the antiproton source service buildings.

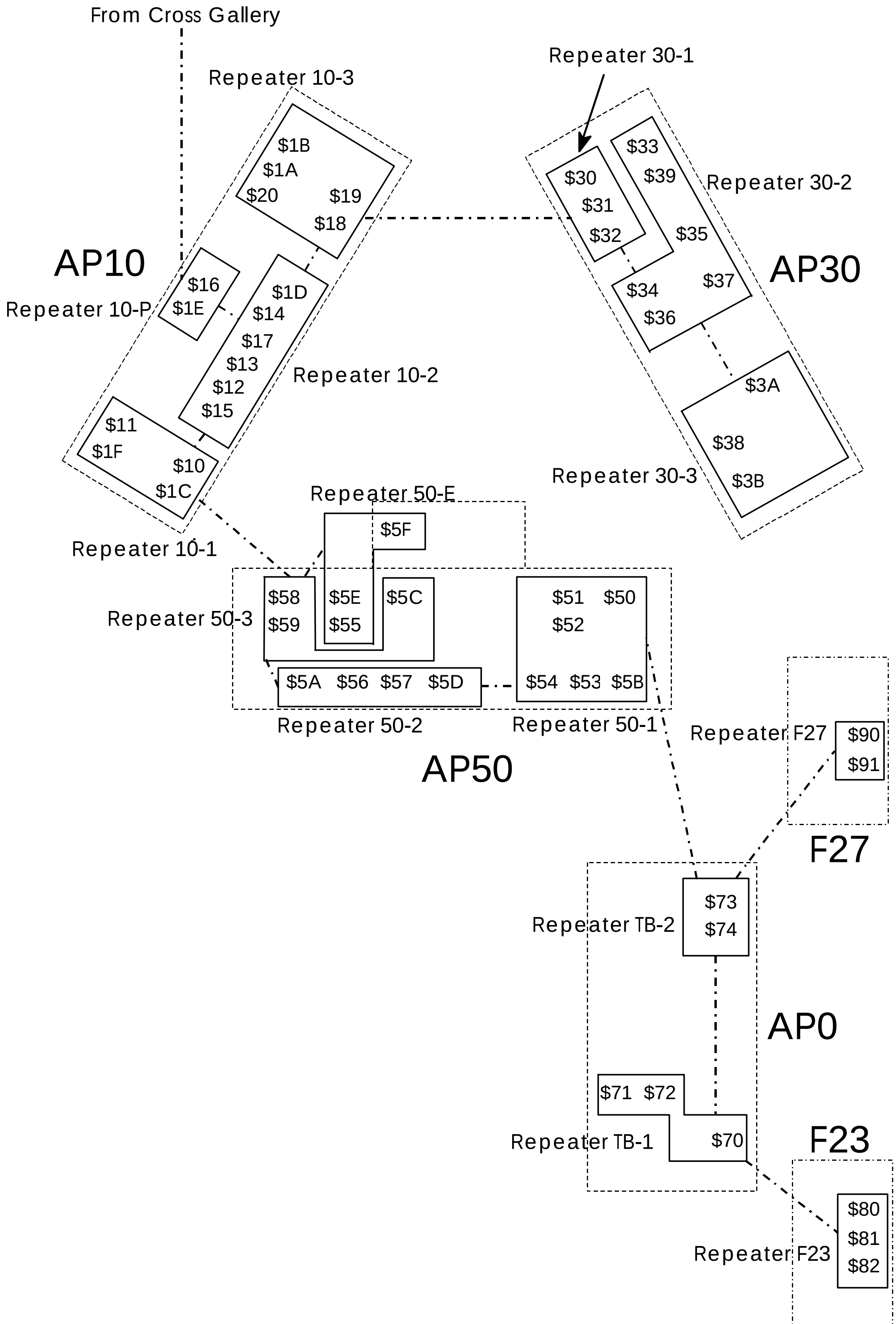

Figure 8.5 Pbar Source CAMAC Serial Link

IX. Modes of operation

The Antiproton source can be oriented into several modes of operation based on the needs of users. In addition to antiproton stacking and unstacking, several operating modes were created that utilize protons. Protons provide a convenient source of relatively high intensity beam for tune-up and studies. The antiproton source has even been used to provide beam for experiments housed in the A50 pit. Each mode of operation that has been used to date is summarized below with the exception of transfers from Booster using the decommissioned AP-4 line.

A. Antiproton stacking

A single Booster batch is accelerated in the Main Injector to 120 GeV. After the protons are bunch rotated, the short bunch length beam is extracted from the Main Injector. Beam is transported down the P1 and P2 lines, then is directed at F-17 into the AP-1 line (see figure 9.1). The protons move down the AP-1 line into the target vault where the beam strikes a nickel target. Downstream of the target, 8 GeV antiprotons, as well as other negative secondaries, are focused with the collection lens and are momentum selected with the pulsed magnet. Particles that are off-momentum or positively charged are absorbed in a beam dump. The secondary beam travels to the Debuncher via the AP2 line where most of the non-pbar secondaries decay away. Of the remaining secondaries, most are lost in the first dozen turns in the Debuncher. Only the small fraction of antiprotons with appropriate energy survive to circulate in the Debuncher. For every million protons on target, only a dozen or two antiprotons make it

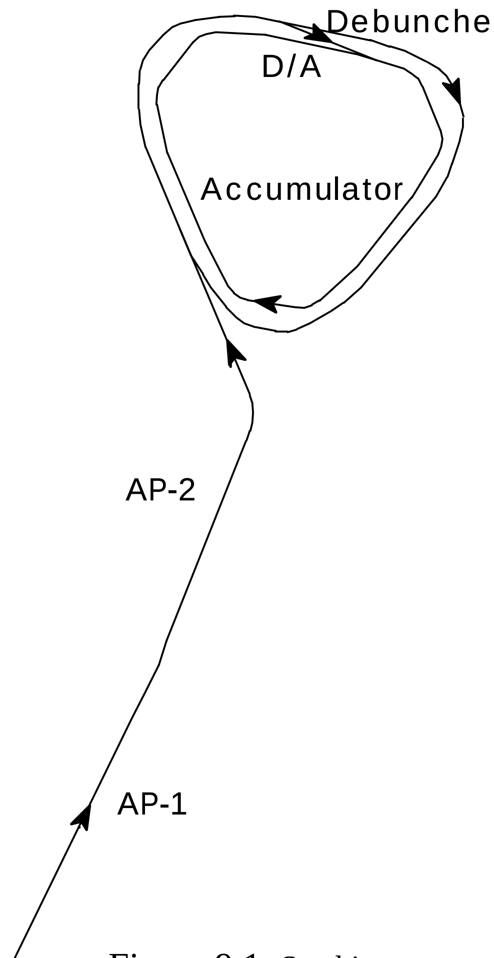

Figure 9.1 Stacking

to the core. After debunching and cooling in the Debuncher, the pbars pass through the D to A line and into the Accumulator. Successive pulses of antiprotons arriving into the Accumulator are 'stacked' over several hours or days into the core by ARF-1 and stochastic cooling. Significant TCLK resets are Booster $14, Main Injector $29, Debuncher $81 and Accumulator $90. Stacking cycles are at least 1.5 seconds in duration and may be extended to improve the stacking rate with larger stacks.

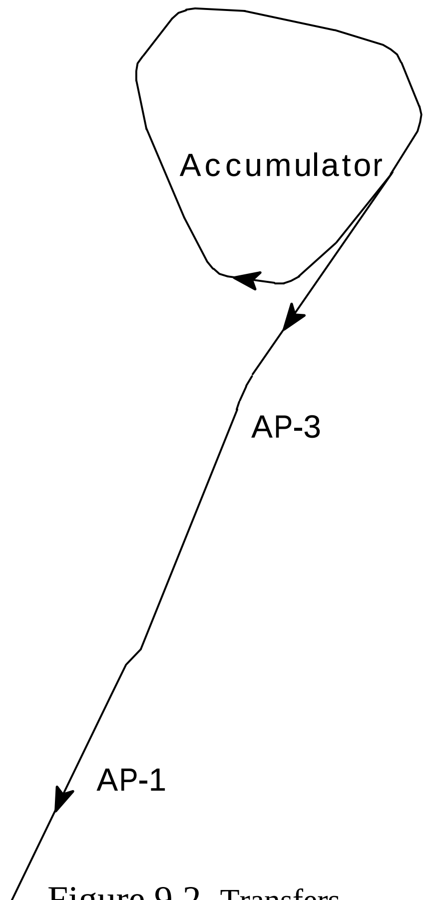

Figure 9.2 Transfers to Main Injector

B. Antiproton transfer

Pbars are unstacked from the Accumulator core with ARF-4 and accelerated to the extraction orbit. The ARF-4 voltage is increased to narrow the bunch, then ARF-1 is turned on to impart a 53 MHz structure on the beam. The Accumulator extraction kicker imparts a horizontal oscillation on the beam so that it passes through the field region of the extraction lambertson. The beam is bent upward by the lambertson and a C-magnet into the AP3 line (see figure 9.2). The beam continues down the AP-3 line, skirting the target vault, and enters the AP-1 line (running at lower currents for 8 GeV operation). The AP-1 line connects to the P2 line at F17 where 2 Lambertsons and 2 C-magnets bend the beam upward to the trajectory of the old Main Ring. Beam continues down the P2 and P1 lines, and is injected into the Main Injector. Significant TCLK resets are: Main Injector $2A and Accumulator $90 and $9A.

C. Reverse protons

Protons from the Booster are transferred to the Main Injector where their energy remains at 8-GeV until transferred. The protons trace the reverse path of the beam in an antiproton transfer. Beam is extracted into the P1 line, then continues down the P2 line until entering the field region of the F-17 lambertsons. The two lambertsons as well as two C-magnets bend the beam upward into the AP-1 line. The beamline is configured for 8 GeV operation by running the magnets from a separate set of power supplies. EB6 (powered by D:H926) bends beam into the AP-3 line, EB5 and EB6 make up a dogleg that diverts beam along the outside of the vault. After passing through AP-3 the beam continues through a C-magnet and the field region of the extraction lambertson which bends the beam upward into the Accumulator at A30. The extraction kicker in A20 deflects the beam horizontally onto the closed orbit of the Accumulator.

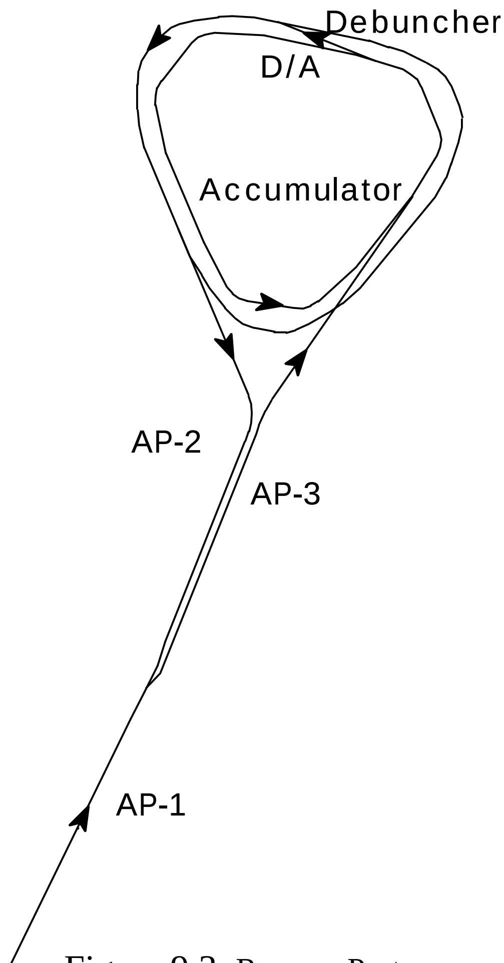

Figure 9.3 Reverse Protons

Reverse proton mode compliments stacking in that the polarity of the Rings and beamlines do not need to be reversed. Reverse protons are used in Collider mode to tune up the AP-1 and AP-3 lines prior to an Antiproton transfer from the Accumulator to the Main Injector. Reverse proton mode is also used for high intensity studies in both rings and all beamlines. If desired, particles can be extracted from the Accumulator and sent down the D to A line into the Debuncher. Beam can then be injected backwards into the AP-2 line and transported to the target vault. Significant TCLK resets are a Booster $16, Main Ring $2D, and an Accumulator $93.

D. Forward protons

8 GeV protons are extracted from the Main Injector and continue into the AP-1 line in the same manner as in reverse proton mode. The similarities end there as beam is directed to the target vault instead of into the AP-3 line (see figure 9.4). In the target vault the production target and collection lens have been pulled out of the beamline and the polarity of the pulsed magnet has

been reversed. The rings, and beamlines downstream of AP-1, have had their polarities reversed. This way the 8 Gev protons can continue into the AP-2 line, the Debuncher, the D to A line and the Accumulator as required. The proton beam could also be injected into the AP-3 line but it is normally more convenient to use reverse protons.

Forward proton mode can be useful for phasing cooling systems using higher intensity beams and other direction-specific studies in the source. This mode is most commonly used at the beginning of a running period to phase in the Debuncher cooling. Significant TCLK resets are a Booster $16, Main Ring $2D, and a Debuncher $85.

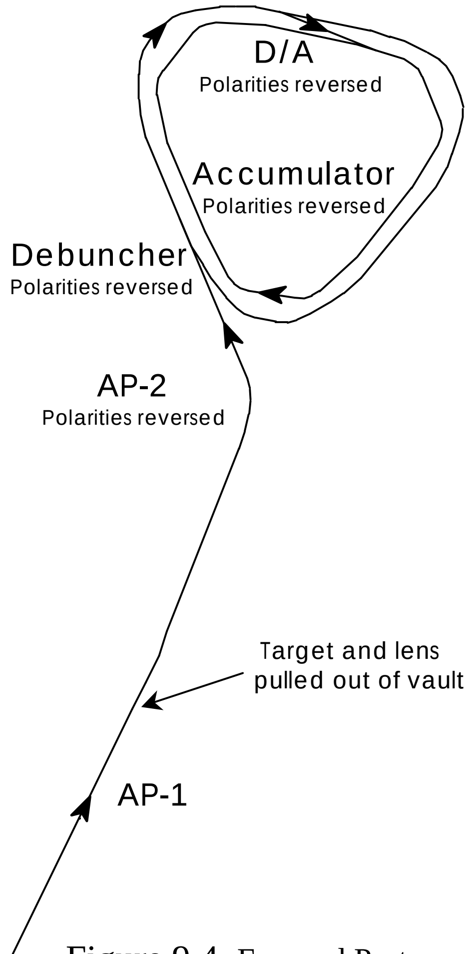

Figure 9.4 Forward Protons

E. Proton stacking

In proton stacking mode the beam follows the same path as in antiproton stacking, but proton secondaries instead of antiproton secondaries are stacked (see figure 9.5). To accomplish this, polarities of components downstream of the target are reversed. In the target vault, 8 Gev protons are focussed, then charge and momentum selected because the polarities of the collection lens and pulsed magnet are reversed. The polarity reversal not only includes the rings, AP-2 and the D to A line but also the dampers and stochastic cooling systems.

Proton stacking has been used to test the limits of the stacking rate by stacking secondary protons instead of antiprotons. Proton secondary flux to the Debuncher is about six times greater than that achieved with antiprotons. This is particularly useful for testing cooling systems under conditions simulating increased intensity. Proton stacking studies at the end of Collider Run 1b attained a peak stacking rate of 12.2 E10/hr (as opposed to 7.3E10/hr for antiproton stacking earlier in the run). Significant TCLK resets are the same as during stacking, a Booster $14, Main Ring $29, and an Accumulator $81.

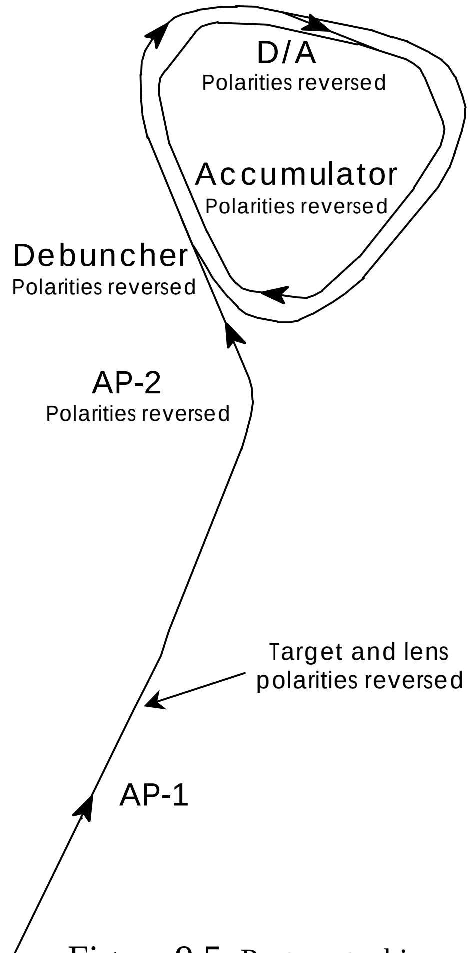

Figure 9.5 Proton stacking

F. Deceleration

In 1986, an experimental pit adjacent to Accumulator straight section 50 and a counting room attached to AP50 were constructed. The pit and counting room were built to provide space for experiments interested in using circulating Accumulator beam. Experiment E760 was the first to make use of the new facilities. The goal of the experiment was to measure the mass and width of charmonium states by means of $\overline{p}$ - p collisions. A charmonium state is produced when a charm and anti-charm quark pair are produced and bound together, briefly orbiting each other. The quark pair is very short-lived, decaying in only 10^{-20} seconds. The angular momentum from the spinning quarks contributes to their total energy. There are a number of different charmonium states defined by the rate at which the quarks rotate around each other.

The main components of E760 were a hydrogen gas jet target, which was the source of the protons, a particle detector, and the Accumulator, which provided the antiprotons. The gas jet target provided an interaction region of roughly one cubic centimeter. Circulating antiprotons in the Accumulator pass through the gas jet and some fraction of them interact with the hydrogen.

The Accumulator was modified to serve as a decelerator to reach the necessary energies, the lowest of which is at 3.770 GeV. Some of the desired resonances are located below the transition energy of the Accumulator. To reach these energies beam must be decelerated below transition. To accomplish a deceleration, all power supplies and an appropriate RF system were ramped down in a very precise fashion. Because the velocity of the beam was reduced during deceleration, the cooling system delays were also shortened to maintain the proper phasing. Quadrupoles, sextupoles and octupoles were also ramped to keep the tunes safely away from resonances. Special code in the pbar front end provided the ramp waveforms necessary for the deceleration.

The beam is kept on the central orbit so that it is centered in the aperture in high dispersion regions. A new set of 2-4 GHz core momentum pickups were added that were sensitive to beam on the central orbit. The pickups used during collider operation are located at the core and were not suitable for beam on the central orbit. The 4-8 GHz core momentum pickups were mounted on a motorized stand and could be moved to the central orbit.

The E760 run took place during the 1990 Fixed Target run with the Antiproton Source dedicated to running the experiment. A typical sequence of events was as follows: a period of stacking to accumulate several 10E10 of pbars with the stacking cycles occurring in the 56 seconds between Tevatron injections. After the appropriate number of antiprotons was stacked, physicists and operators decelerated the beam from the MCR in a fashion similar to a shot set-up in Collider operation. After the deceleration was completed the experiment would conduct hours or days of data taking after which the cycle would repeat.

Experiment E835 was a progression of E760 and took data during the 1996-97 Fixed Target run. Among the improvements for E835 was an upgraded detector with a liquid Helium cooled calorimeter, which required a stand-alone Helium refrigerator at the AP-50 service building. This prompted the relocation of the A:QT power supply from AP-50 to AP-10 to provide room. Control of the deceleration ramps was integrated into the Pbar front end instead of an auxiliary front end as was done with E760. E835 was primarily interested in improving their statistics on the 1P1 resonance and also attempt to observe the Eta c' resonance which had never been observed.

E862 ran in parallel with E835. The experiment was involved with measuring anti-Hydrogen atoms created by the E835 gas jet. A separate beamline extended into the tunnel aisle downstream of A5B3. The beamline included a table that contained a stripping foil, magnets and a positron detector. Downstream of the table was a pair of dipole magnets and three wire proportional chambers, with the line ending with an antiproton detector.

When the Hydrogen jet interacts with the antiproton beam in A50 there are occasions when anti-Hydrogen is produced. The anti-Hydrogen, which is neutral, is not bent by the A5B3 dipole and passes into the experimental beamline. At the table a stripping foil separates the positron from the antiproton. The particles pass through a small dipole, which bends the less massive positrons into a separate beamline that terminates in a positron detector. The antiproton continues down the beamline and passes through the two dipoles, eventually entering the antiproton detector. Experimenters hoped to measure the production rate and spectroscopy of anti-Hydrogen.

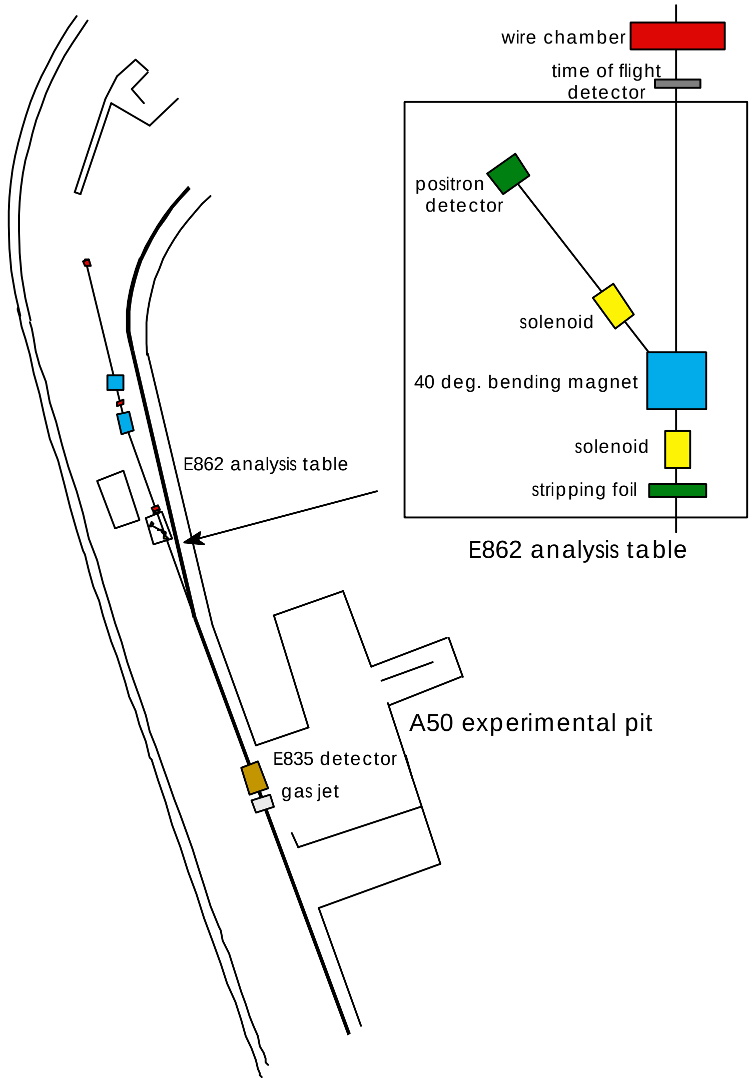

Figure 9.6 E835 and E862

Not all experiments require a dedicated running period during Fixed Target operation. During collider run 1b experiment E868, also known as APEX (AntiProton EXperiment), had a successful run. Their goal was to make a lower estimate of the lifetime of an antiproton. Most of their data-taking time was during stacking downtime or during shot set-ups.